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S E S S I O N 1

CIMP and System Integration/ SIMM et l'intégration

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INTRODUCTION TO COMPUTER INTEGRATED MATERIALS PROCESSING (CIMP)

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INTRODUCTION:

CIMP technology focuses on the integration of all design and manufacturing functions with the ability to simulate what is happening in a process and to use this information in the design phase of a given product and associated tools. This will result in a better product/process definition as well as generating the appropriate instructions for the production equipment. This article should be of special interest to all industry sectors such as raw material suppliers, processors, equipment manufacturers, die and mould makers.

The technology will assist in the development and adaptation of existing or new materials and processing techniques, to meet the challenge of today's productivity and product requirements. The research work described in this article should enlarge the technological perspective of advanced materials and stimulate their introduction into sophisticated products for the benefit of the automotive, aerospace, electronic and electromechanical industries.

1) SYSTEM INTEGRATION

There are three integration levels built into the CIMP concept. The first integration level is generic and deals with several engineering functions. Figure 1 shows this concept articulated around solid modeling technology and a common database. The challenge is to incorporate the various functions involved in the product development cycle, such as product/process definition, material selection, process simulation, product performance evaluation, process planning and production control, into a single integrated environment.

The second integration level is specific to the elements of a given manufacturing process. As presented in figure 2, CIMP technology implies the interactivity between different fields of expertise such as materials, tooling, processing and product engineering as well as the mathematical modeling of the physical changes that occur during production and under service conditions. For example, a computer integrated injection moulding network means a way of efficiently chaining together interrelated technologies such as moulding, polymer engineering, product design and mouldmaking [1].

The third integration level, shown in figure 3, is concerned with the meshing of the previously developed integrated systems at the plant level, since there is an interrelationship between the various forming processes and their associated materials. It will be possible to speed up the integration work through the individual applications, because the basic principles of CIMP technology can be applied to different processes.

Whatever we call it, either design for manufacturing or simultaneous engineering, the question is how to replace the traditional sequential flow of information by concurrent and iterative procedures where different functions exchange information and perform the work at the same time. A typical example is shown in figure 4 for product/process design and optimization.

We must learn about the domain of the application and about the product development cycle itself. Extensive research has been done at the Industrial Materials Research Institute on the application of CIMP technology in the areas of injection moulding, die casting, extrusion and blow moulding [2].

2) PRODUCT AND PROCESS DEFINITION

Figure 5 presents a typical main menu that allows the user to access the most important functions required in the integrated environment. The user begins by gathering product information to define the specifications (structural requirements and service performance). A generic problem solving architecture has been designed and incorporated into the system. The decision making process is related to some concepts of acceptability. Furthermore, a compatibility with previous decisions must be maintained.

The system keeps reference to a set of material dependent design guidelines while assisting the user in the selection of appropriate material/process from the database. The preliminary selection may later be modified depending on the results of process simulations. In order to develop a reliable model of the part, the user must have access to a comprehensive database that can provide not only the standard material properties but also all data pertaining to their variations within the range of the production parameters [3].

A tridimensional description of the object to be produced is shown in figure 6. One can see a logical relationship between the major steps of a product development cycle and their associated material databases. This relationship is best illustrated by the development of knowledge based parametric databases. For example, figure 7 illustrates a parametric design capability for the most common delivery channels, (sprues, runners and gates) by taking into account the processing requirements and material

characteristics. This will speed up subsequent steps such as mould filling simulation, machining simulation, calculation of the weight of the complete shot and production costs [4].

A preliminary structural analysis should be performed to establish the wall thickness and the principal dimensions of the product. Occasionally, this analysis may reveal a need for basic conceptual design changes to prevent serious design flaws and minimize subsequent modifications in the following simulation steps.

3) PROCESS MODELING AND SIMULATION

In order to achieve this integration level, the interaction between material behaviour and process technology must be taken into account on a process basis as shown in table 1. Also, several modeling techniques are required in a variety of engineering fields such as computer graphics, process and material technology, decision making, etc. A partial list of these modeling techniques is given below:

-Tridimensional geometric modeling (Wireframe, solid modeling)
-Modeling of material properties in liquid and solid states
-Modeling of material behaviour under service conditions.
-Modeling of material structure and interactions (Molecular mechanics)
-Process modeling (Moulding, forging, casting,machining, etc)
-Modeling of material flow (Scheduling, manufacturing routing)
-Interactive modeling of information flow and decision making process
-Modeling of process control (Transfer functions for controllers of vision systems, robots and sensors)
-Modeling of production costs

For example, some models describe the melt flow pattern, stresses, pressure and temperature variations during the moulding cycle [6]. Figure 8 shows a typical filling pattern. Others describe the solidification, curing or the shrinkage of the material. Possible weaknesses due to the formation of voids, weldlines and sink marks can be corrected by optimizing the operating conditions and the part/mould geometry. Part warpage and residual stresses due to the different cooling rates in distinct regions of the part can be minimized. The mould cavity and core can then be modified to compensate for moulding shrinkage and produce parts to specifications.

At this stage, the user can complete the detail drawing of the product and the tooling, (see figure 9) then he may proceed with the machining simulation. By establishing a proper sequence of operations during this development phase, considerable time and cost savings can be achieved. Since the process is

interactive, constant feedback must be given at all steps. The simulation will end when the optimum operating conditions as well as the production requirements have been met.

4) PRODUCT AND MATERIAL PERFORMANCE EVALUATION

The information generated in the previous steps can be used to check for possible modifications of existing materials or to develop new materials, alloys and composites and test their performance in a specific application. This insures that material performance meets product requirements not only under the service conditions but also from a processability point of view.

At this stage, a true finite element structural analysis can be performed on the simulated product if necessary. Instead of working on the geometry of the product as has been discussed previously using isotropic material properties, it is now possible to carry out a refined analysis using corrected local material properties taking into account the effect of processing conditions.

For example, the user can access interactively the results of the filling and cooling simulations to evaluate problem areas in different regions of the model. Basically, three major classes of problems can be investigated:

- -Problems related to processing conditions.
- -Problems related to part and mould design.
- -Problems related to material behaviour.

Figure 10 shows the main menu of an expert system for the design analysis and optimization of moulded products. A finite element model can then be generated on the basis of this analysis. Ultimately, the interactive session will produce realistic variations of mechanical properties throughout the moulded part. Naturally, this analysis can be limited by the availability of the constitutive equations that describe the relationship between the mechanical properties and the processing conditions [5].

For the part shown in figure 11, four distinctive regions (gate, weldline, cylinder, top of part) were investigated during the evaluation of material properties. Tables 1 and 2 show the variation of properties in the range of operating conditions and a comparison between isotropic and anisotropic behaviour. The stress level is of the same order of magnitude for both calculations; however, the maximum displacement is not the same. Since the yield strength is different for the isotropic and anisotropic cases, a different safety factor will result. If the anisotropic analysis is not performed, the safety factor based on the isotropic analysis will depend solely on the processing conditions. If the lower limit is used during the moulding operation, the real safety factor will be much lower than the

calculated one and the part will fail .

CONCLUSIONS

This article has illustrated the CIMP concept in different ways. The implementation of this technology is more than a simple matter of wiring and interfacing. CIMP incorporates various functions into a logical network that defines and streamlines the flow of information for a specific manufacturing process. We have seen the advantages that concurrent and iterative design procedures bring to the product development cycle when using interrelated technologies such as advanced materials science, manufacturing technology, process simulation and system integration. We hope that the work described in this article will serve to bridge the existing gap between the product oriented finite element analysis programs and the process oriented simulation programs.

REFERENCES

[1] Girard P., Salloum G., Dion P., "A highly integrated software for injection molding. A case study". 4th Canadian CAD/CAM Robotics Conference, Toronto, Ontario, 18-20 juin 1985, pp. 6.5-6.10

[2] Kappel V. V.; Salloum G.; Connelly R.; Van Hoenacker Y.; "Applications of computer integrated material processing to the die casting, forging and rolling industries."; 7th Canadian CAD/CAM and Robotics Conference, Toronto, June 1988, pp. 6.1-6.8.

[3] Salloum G.; Girard P.; Raducanu P., "Un système expert pour la mise en forme des matériaux", Revue l'Ingénieur, Mai-Juin 1987, pp. 22-27.

[4] Salloum G.; Charland D.; Brouwers X.; "Plasfeed, an interactive design software of feeding system for injection mold using solid modeling"; Annual Technical Conference of the Society of Plastics Engineers; May 1986; Boston, Mass.; pp. 1412-1418.

[5] Salloum G.; Garcia-Rejon A.; Connolly R.; Laguë G.; "A new method to predict the structural stability of injection moulded parts. A combination of flow simulation and finite element stress analysis techniques."; Annual Technical Conference of the Society of Plastics Engineers; Atlanta, May 1986, pp. 285-289.

[6] Schacht T.; Menges G.; "Studies and simulations on flow behaviour in injection moulding"; Annual Technical Conference of the Society of Plastics Engineers; Washington, May 1985; pp. 805-808.

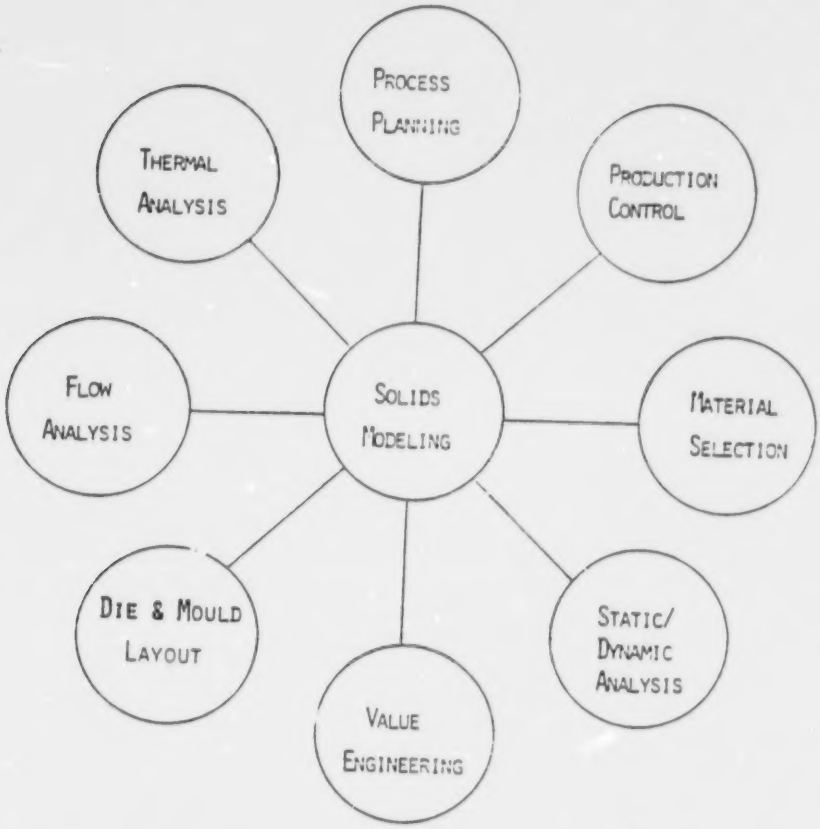

Fig: 1 Computer Integrated Product Development

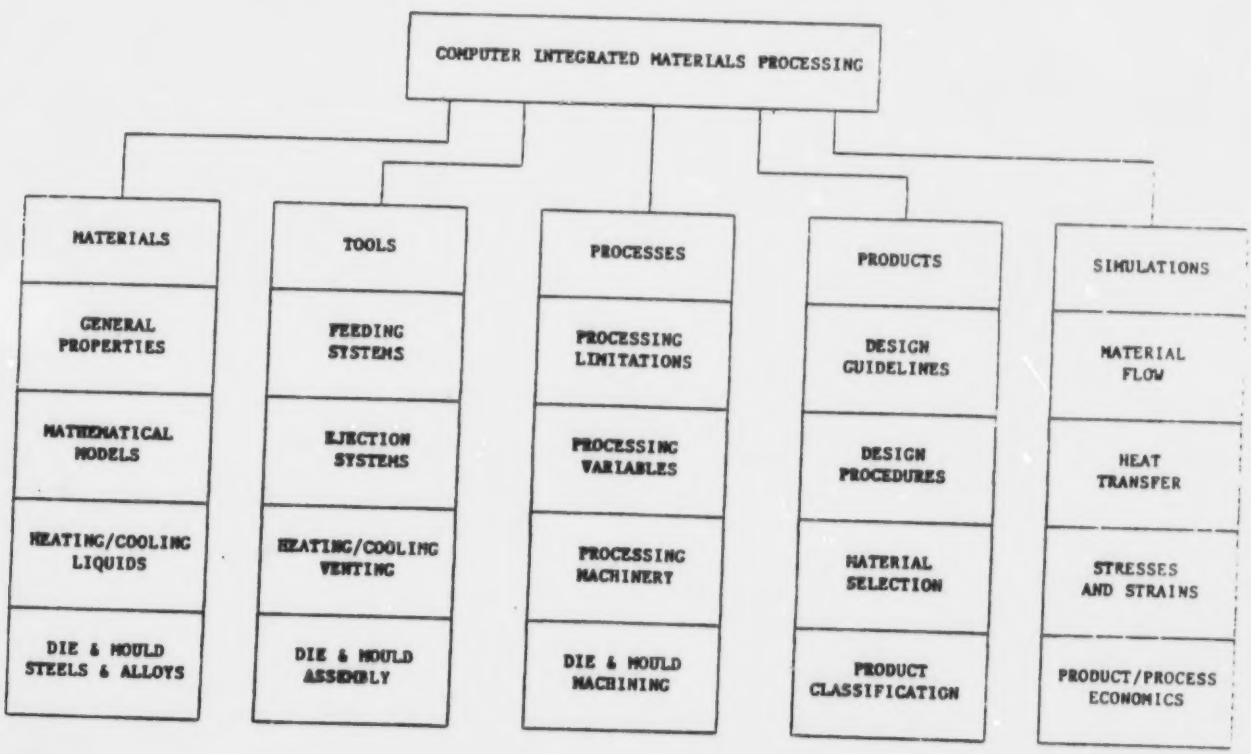

Fig: 2 Interrelationship Between Various Fields of Technology in CIMP

Processes \ Materials			Plastics, Blends and Composites	Elastomers and Blends	Metals Alloys and Composites	Ceramics Metal-Powders Composites
Injection Moulding			O	O		O
		Die Casting			O	O
	Extrusion		O	O	O	O
		Blow moulding	O			O
Compression Moulding			O	O		O
	Forming		O		O	
		Forging	O		O	O

Fig 3: Inter-relationship between various material forming processes

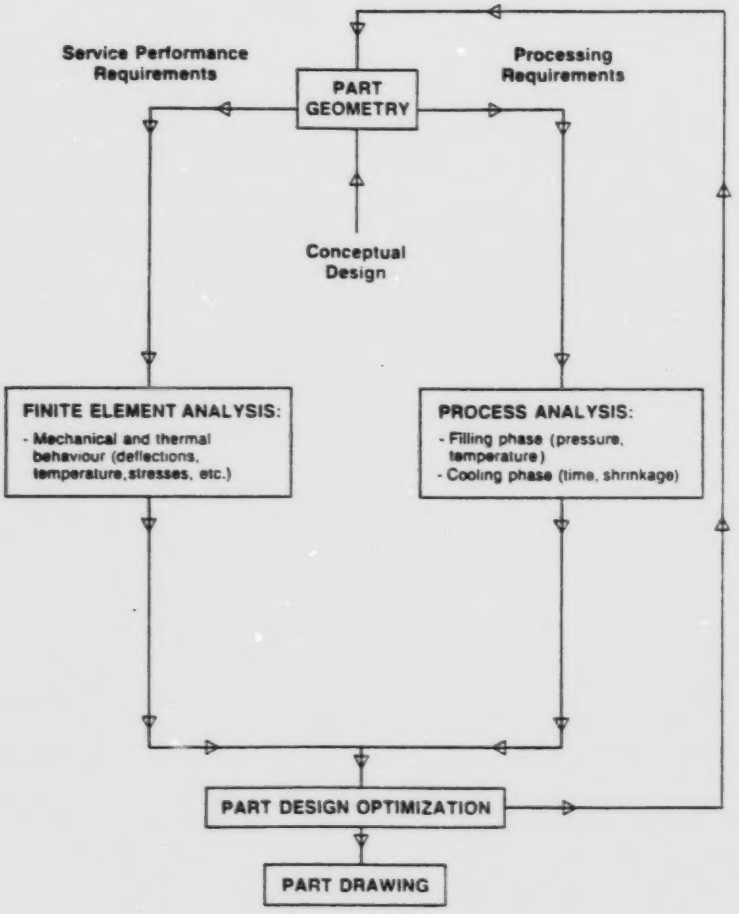

Fig: 4 Part Design Optimization by Considering the Effects of Material Processing and Service Requirements

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MAIN MENU
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 1 = PRODUCT INFORMATION
 2 = MATERIAL DATA
 3 = MATERIAL SELECTION
 4 = DATA HANDLING
 5 = SOLID MODELING
 6 = MODELING FOR FILLING SIMULATION
 7 = FLOW SIMULATION
 8 = DESIGN OF FEEDING SYSTEM
 9 = THERMAL SIMULATION
10 = FINITE ELEMENT MODELING
11 = MECHANICAL SIMULATION
12 = MOLD DESIGN
13 = MACHINING SIMULATION
14 = TECHNICAL AND ECONOMICAL ANALYSIS
15 = INTERFACES
16 = END
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Fig. 5: The main menu for CIMP

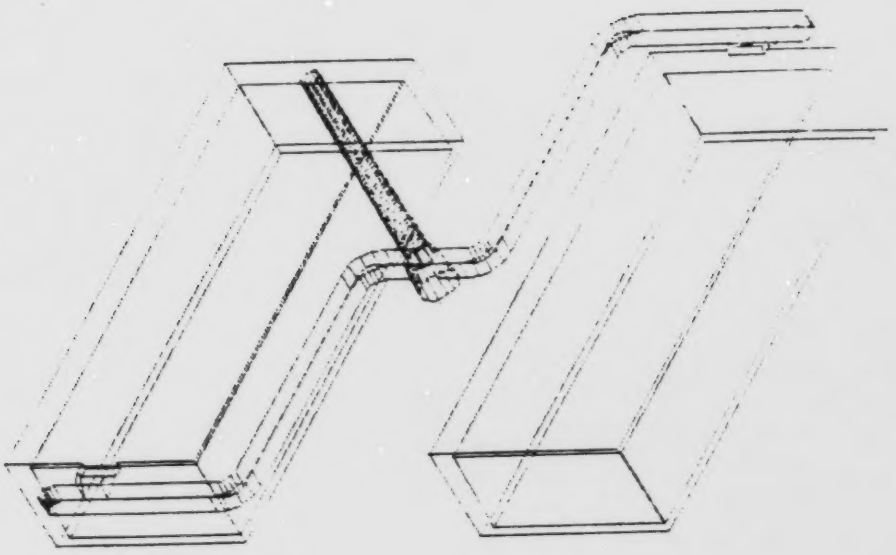


Fig: 6 3D Representation of the Part

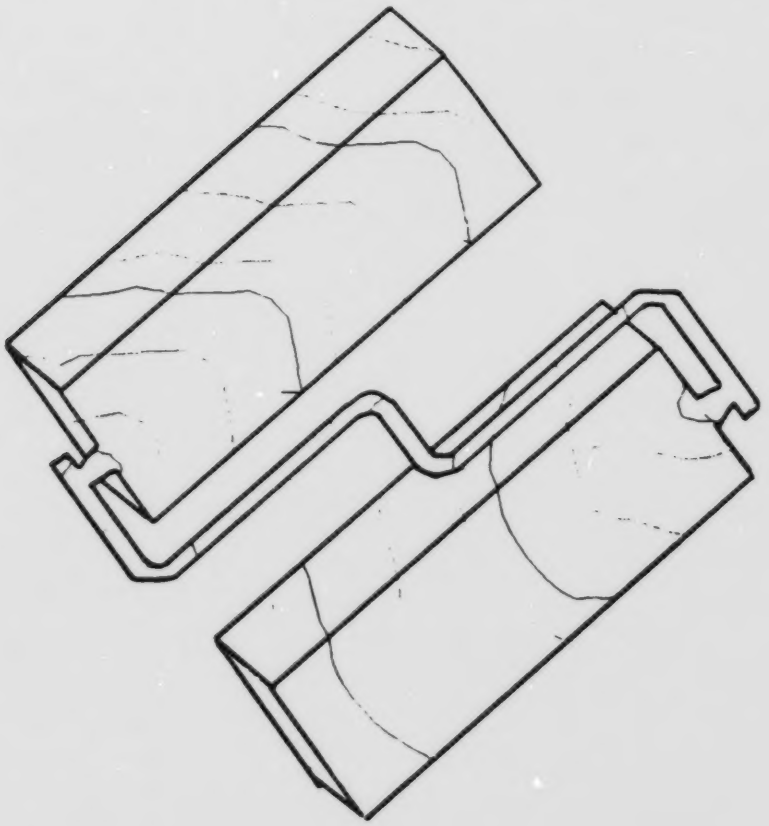
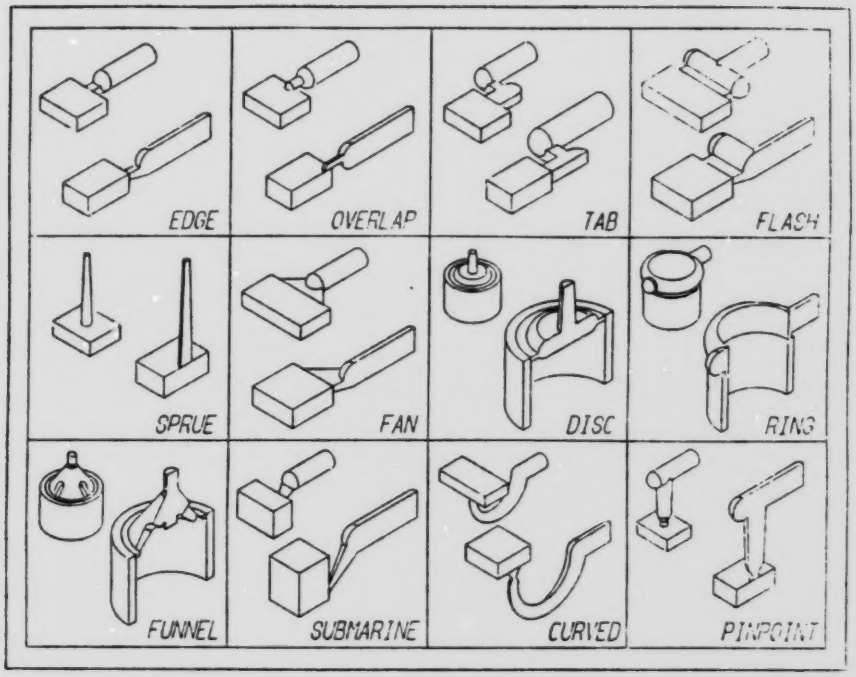


Fig: 8 Filling Pattern



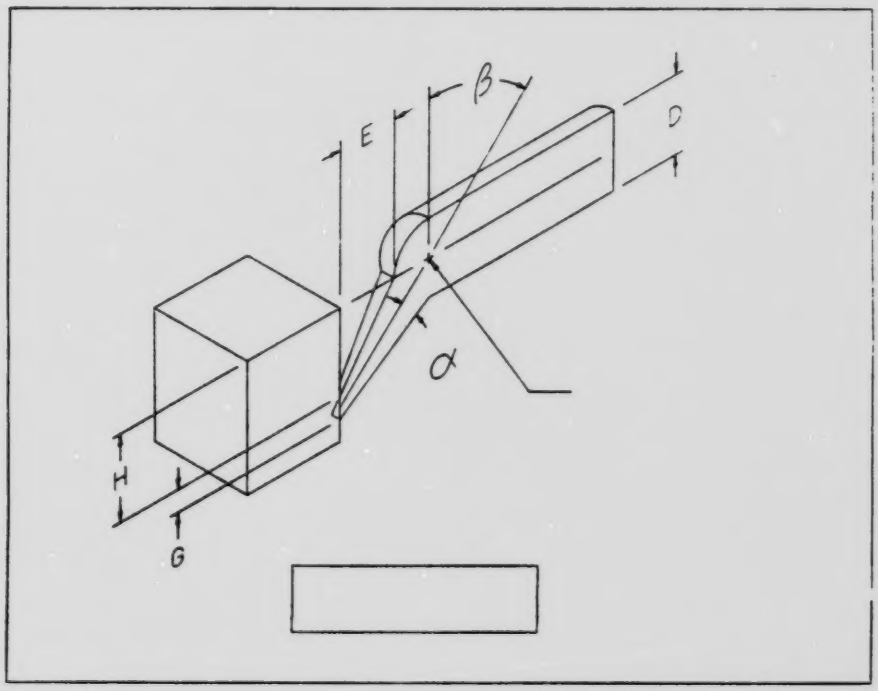


Fig: 7 Parametric Design of Delivery Channels

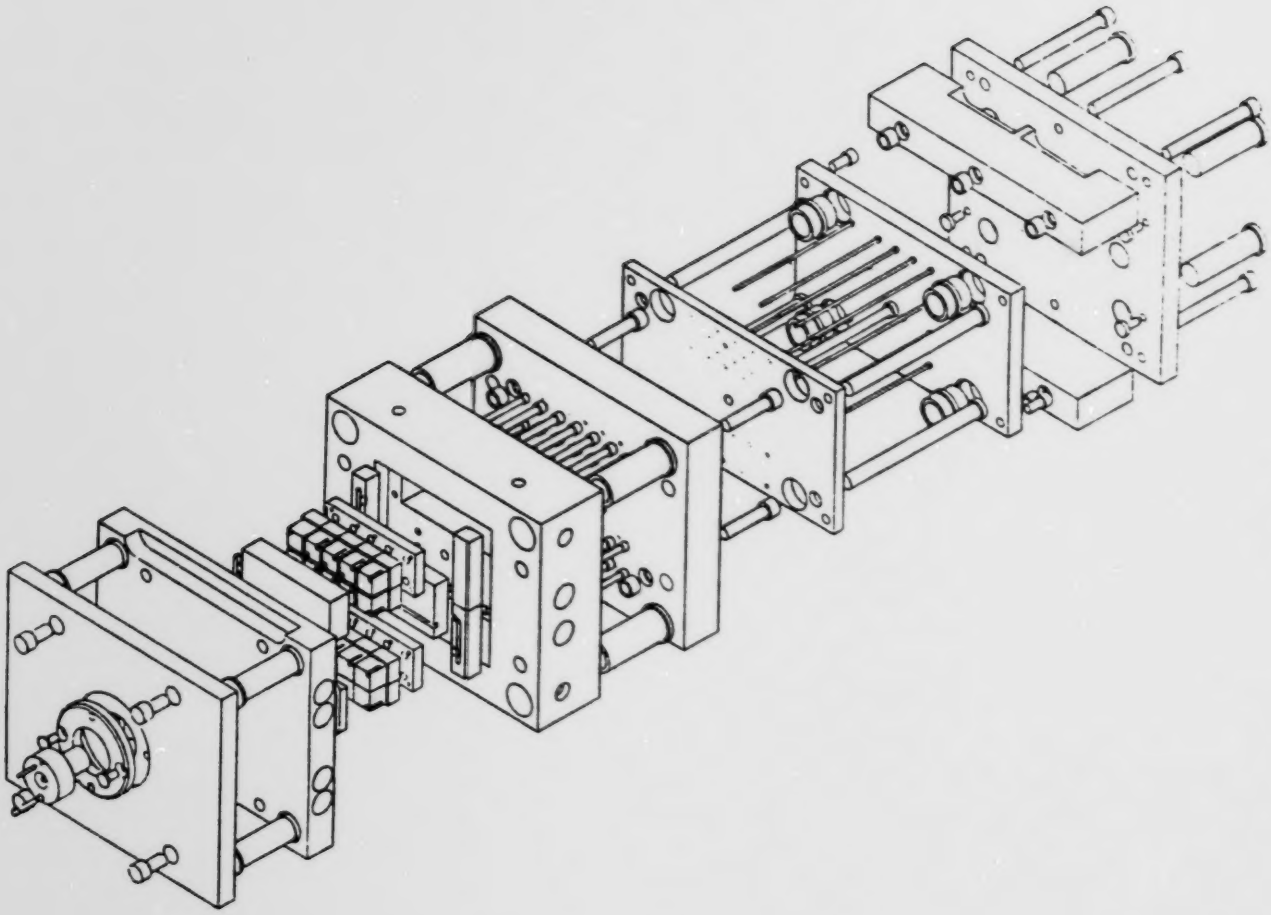


Fig: 9 Detail Drawing of the Mould

PLASFEM MAIN MENU	NAME OF SUBMENU	HELP MESSAGE
	PART GEOMETRY	Partionning of FLOW PATTERN into specific regions to analyse such as gates, weldlines, high shear stress area (melt), etc.
	MOULDING PROCESS	Effects of processing parameters used to mould the part.
	MOULD DESIGN	Effects of the mould geometry and of particular mould design aspects such as: size, orientation, gating, etc.
	MATERIAL BEHAVIOUR	Environmental conditions sustained by the part such as: humidity, UV ray, and annealing, etc.
	SERVICE CONDITIONS	Service conditions sustained by the part such as: loading type, pressure, temperature, etc.
	FEM PROCEDURE	Procedure to achieve a proper FEM (Finite Element Modeling) and stress analysis of the part.
	RESULTS INTERPRETATION	List of main criteria to satisfy (stress, strain, displacement, etc.).
	EXIT	Return to main menu. Possibility to modify any data to PLASFEM.
	HELP	Provide information of any chosen topic of this menu.

Fig:10 Expert System for the Design Analysis of Moulded Products

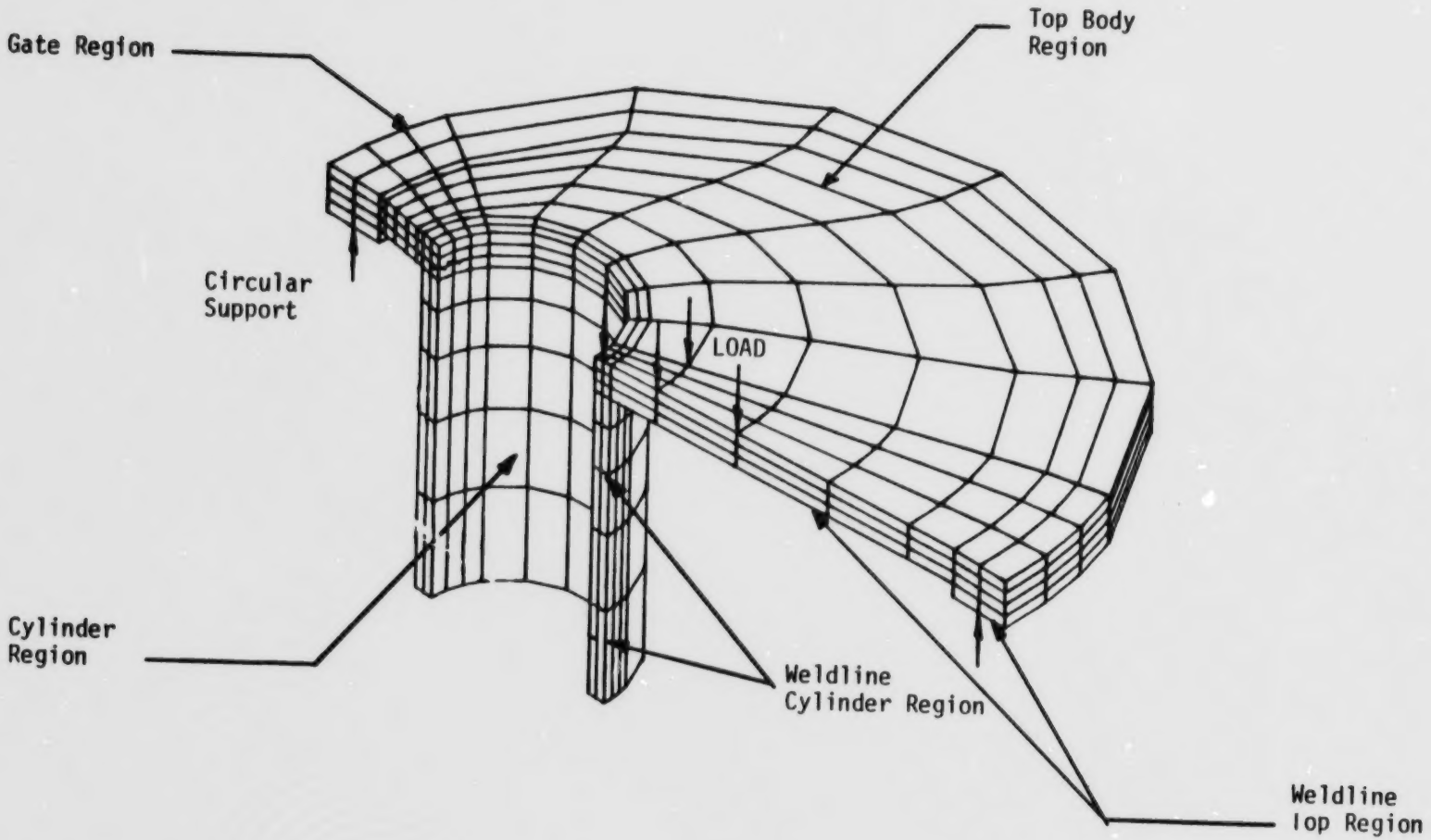


Fig:11 Analysis of Part with distinct Regions

Mechanical property	Region 1 Top Body	Region 3 Gate	Region 3 Cylinder Weldline	Region 4 Cylinder	Region 5 Top Body Weldline
Elastic Modulus (Ksi)	126 180	120 170	93 118	116 148	122 144
Yield Strength (Ksi)	2. 1 2. 35	2.0 2.25	1.2 1.25	1.6 1.8	1.65 1.88

Loading speed = 5 mm/min.
Service temperature = 70 °F
Melt temperature = 370-480 °F
Mold temperature = 70-130 °F
Moulding pressure = 5 - 12 Kpsi

Isotropic behaviour
Elastic Modulus : 153.7 Ksi
Yield strength : 2.33Ksi

Table 1: Anisotropic Variations of material properties of HDPE with processing conditions (See Fig: 11)

Von Mises Stress/ Displacement	Region 1 Top Body	Region 3 Gate	Region 3 Cylinder Weldline	Region 4 Cylinder	Region 5 Top Body Weldline
Max. Stress Isotropic (Ksi)	1135	464	664	473	1335
Max. Stress Anisotropic (Ksi)	1139 1165	470 474	570 520	466 435	1316 1254
Maximum Displacement Isotropic (In)	0.069	0.027	0.106	0.106	0.069
Maximum Displacement Anisotropic (In)	0.086 0.061	0.033 0.024	0.130 0.094	0.130 0.094	0.086 0.062

Applied Force= 550 lbf

Table 2: Comparison between isotropic and anisotropic behaviour for the range of mechanical properties of table 1.

La technologie SIMM appliquée au moulage par injection

par

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Depuis sa fondation en 1939, IPL s'est hissée au premier rang dans la fabrication par injection de produits de matières plastiques dans les domaines de l'emballage, de la manutention et des articles ménagers. IPL développe, fabrique et commercialise ses propres produits destinés principalement à l'industrie agro-alimentaire et chimique.

Son dynamisme, allié au capacités de production très diversifiés dont IPL a su se doter, a permis à l'entreprise de développer d'autres secteurs d'activités, notamment celui relié au domaine du transport dont Ford et Mazda.

La direction de IPL a toujours favorisé l'acquisition des dernières technologies dans le but d'accroître la qualité, la productivité et des emplois de plus en plus valorisant pour son personnel. C'est ainsi que depuis le début de cette décennie nous avons entrepris un projet global d'informatisation de tous les départements pour arriver en 1990 avec une entreprise totalement intégrée de la conception à la livraison chez nos clients.

Le présent document traitera des quatre secteurs fondamentaux qu'il faut obligatoirement développer pour arriver à concrétiser une industrie super efficace qui a comme mandat premier la satisfaction de sa clientèle par un service et un produit de la meilleure qualité. C'est ainsi que IPL s'est méritée la mention Q1 de la compagnie Ford pour son excellent dossier de qualité, de livraison et de service. Notons aussi le Mercuriade de la Qualité Totale dans la section des grandes entreprises pour 1988.

Ces quatre secteurs sont: matériaux de pointe
technologie de fabrication
simulation des procédés
intégration des systèmes

Chacun sera défini dans l'environnement actuel de IPL et il y aura aussi une certaine projection vers le futur pour mieux cerner le but à atteindre.

Matériaux de pointe

Comme il s'avère véridique que les années 90 seront centrées sur le développement de nouveaux matériaux et que les plastiques en prendront une large part, il est donc indispensable de travailler avec des résines de très haute qualité et de propriétés adaptées à l'application.

Actuellement nous travaillons avec des polyéthylènes, polypropylènes et différentes résines d'ingénierie. Dans le domaine des résines de commodité nous travaillons actuellement avec nos fournisseurs pour développer un écoulement plus élevé tout en maintenant les propriétés mécaniques, physiques et chimiques. Dans le domaine de l'automobile, l'utilisation de résines toujours plus rigide et à haute résistance thermique est requise ce qui fait que nous sommes continuellement à la recherche de nouveaux développements.

Un domaine où nous voulons accroître notre expertise serait dans le contrôle de qualité à la réception. Actuellement ceci ne se fait que par densité et "melt index" qui sont des tests faciles et rapides mais qui ne nous permettent pas de réellement séparer les lots de qualité inférieure. La caractérisation des résines est donc une priorité pour nous car toutes ces données permettront la conception des pièces et des moules plus efficacement et rapidement mais aussi serviront comme base de données pour le contrôle de qualité.

Technologie de fabrication

IPL a toujours été à l'affût des derniers développements technologiques tant au niveau des machines que des moules. Actuellement la majorité de nos presses à injecter sont équipées de microprocesseur et valve proportionnelle et quelques unes fonctionnent en boucle fermée.

La différence entre IPL et ses compétiteurs vient du domaine des moules où nous avons développé une expertise reconnue. Nous travaillons toujours avec des moules de première qualité fabriqués avec les meilleurs aciers. La majorité de nos fournisseurs sont maintenant équipés de CNC ainsi que du système CAO/FAO ce qui améliore la précision et les délais de livraison. Nous avons débuté le transfert des dessins entre notre CAD et les leurs par ligne téléphonique.

Durant les dernières années, une équipe d'automatisation a été créée pour faire l'implantation, la création et la fabrication de robot ou de machine automatique pour des lignes de produit. Le but visé est de diminuer la manipulation répétitive des pièces par les opérateurs, de permettre à une personne de s'occuper de deux ou trois machines (valorisation du travail) et de contribuer à une augmentation de la qualité par un cycle toujour égal et très répétitif. En ce moment 75% des machines en sont équipées et plusieurs importants projets sont en parachèvement.

A partir de la machine, les produits sont acheminés par palette jusqu'au contrôle de qualité par l'entremise de véhicules autoguidés (VAG) qui circulent dans l'usine en suivant des fils dissimulés dans le béton. Cette technologie nous a permis d'éliminer les chariots-élévateurs qui causent souvent des accidents et de produire un flot plus constant de produits au contrôle de qualité.

Si nous regardons plus en détail au point de vue gestion et ordonnancement de la production, IPL fonctionne avec le logiciel MRP II et la banque de données DATA 3. Actuellement toute la cédule de production est émise via le système et toute la planification des matières premières nécessaires avec une livraison dans la semaine. Nous sommes en ce moment à l'implantation de la phase IV qui est la mise en place de toutes les étapes de mise en marché d'un produit ce qui nous amènera à pouvoir savoir à combien se situe le prix de revient d'un produit pour chaque production. Le système "Bar Code" sera utilisé pour faciliter la prise de données.

Il est bien évident que toutes ces technologies sont très utiles mais pour produire une pièce de la meilleure façon possible avec l'équipement disponible, il y a beaucoup de paramètres à ajuster. C'est pourquoi l'on se sert de méthode d'optimisation de procédés telle que TAGUCHI qui nous permet de trouver la meilleure combinaison possible des variables tout en économisant temps et argent mais surtout en augmentant sensiblement la qualité et en éliminant les défauts.

Une prochaine technologie à être implantée au cours de la prochaine année est l'acquisition des différents paramètres de moulage des machines pour faire du contrôle de qualité durant la fabrication. Toutes ces données seront envoyées à un ordinateur central qui les comparera aux tolérances prescrites et s'il y a déviation émettra une alarme. Donc les machines seront suivies vingt-quatre heures sur vingt-quatre et nous éliminerons des rejets dus à l'arrêt de la production sitôt une alarme émise et nous éviterons ainsi des bris majeurs en réparant immédiatement la cause du problème. Notons aussi la possibilité d'obtenir des données de production à chaque instant.

Simulation des procédés

Dans le but de toujours développer des produits de meilleure qualité dans un temps toujours plus court et à un coût compétitif, il fallait se servir de l'ordinateur pour dans un premier temps, accélérer le dessin de la pièce et du moule, puis optimiser celui-ci en simulant à l'aide de logiciels la partie structurelle pour sauver le plus de matière possible et de par ce fait rester compétitif. Notons aussi que le remplissage d'une pièce est toujours très critique car on peut diminuer les contraintes internes de celle-ci en étudiant efficacement la localisation des points d'injection et donc prévenir la distortion ou déformation de la pièce après moulage. Cette étude se fait par un logiciel qui simule en 2D ou 3D l'avance du front d'écoulement en rapport avec les différents paramètres d'injection.

Comme système de CAO/FAO, nous avons le logiciel McAUTO de McDONALD DOUGLAS qui fonctionne sur MicroVax et trois stations de dessin. Dans le domaine des logiciels, ANSYS pour l'analyse structurelle et CAD-MOLD pour le remplissage.

Mais il y a un aspect qui est peu touché en ce moment et c'est la prédiction du retrait pour les pièces par logiciel. Actuellement il y a encore beaucoup d'argent et de temps qui sont perdus dû aux retouches des moules causées par un problème de distortion ou de déformation. Avec l'aide du CNRC et de l'IGM, nous avons un projet global d'optimisation des pièces injectées qui englobe toutes ces étapes de mise au point d'un produit mais dont la partie portant sur la prédiction du retrait est à créer totalement. Nous employons une approche expérimentale par le biais de plans d'expérience portant sur des

géométries simples 2D pour se diriger vers celles plus complexes du 3D. La stratégie actuelle est émise avec l'aide du logiciel RS DISCOVER. Dans un premier temps nous travaillons avec des résines de polyéthylène et une fois que les équations seront validées pour celles-ci, nous nous attaquerons au polypro ainsi qu'aux résines d'ingénierie.

La nécessité d'une approche globale de la conception des pièces, en passant par toutes les simulations possibles sur ordinateur, s'enchaîne dans le processus de produire des pièces qui répondent exactement à ce pourquoi elles ont été fabriquées. Ceci sera bénifique pour une production optimisée et un rapport qualité prix imbattable pour le consommateur.

Intégration des systèmes

Ceci sera probablement l'étape finale au long processus que nous avons entrepris: l'informatisation de l'entreprise. Le but ultime est la véhiculation de l'information le plus rapidement possible et de la manière la plus efficace possible pour aider la prise de décision qui à ce moment sera effectuée à la lumière de toutes les informations pertinentes.

Nous n'avons en ce moment aucun lien entre notre système de CAO/FAO et celui de MRP II ou quelque autre logiciel, à brève échéance il y a un projet en ce sens qui est le transfert d'information d'un cahier de charge informatisé vers MRP II. Ce qui a le plus de chance de se réaliser dans les prochaines années serait le lien entre le logiciel de surveillance des machines et le système MRP II et le lien direct avec des systèmes de nos fournisseurs ou clients pour des prises de commande. Notons toutefois que nous avons quand même intégré des logiciels divers tels que commande, comptabilité, paye, ressources humaines, etc...

En résumé, l'usine future d'IPL sera intimement liée avec tous les autres départements par un échange d'informations extrêmement rapide et une usine avec des employés spécialisés qui entretiendront les diverses machines et robots à l'oeuvre. Par contre pour y arriver, il aura fallu changer bien des règles déjà bien établies et le plus gros défi tant qu'à l'implantation des ces technologies, c'est la formation du personnel en place qui doit se servir adéquatement et comprendre que l'utilisation de celles-ci améliorera leur emploi et surtout les maintiendra dans un environnement toujours plus compétitif.

EXPERT SYSTEMS

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H3A 2K6

ABSTRACT

Expert Systems are defined and compared with conventional Data Processing Systems. Knowledge Representation and Reasoning paradigms are reviewed. Some application areas are discussed.

INTRODUCTION

The following are some of the major topics of Artificial Intelligence:

- Knowledge representation.
- Problem solving and automated reasoning.
- Natural language understanding.
- Computer perception [speech and vision].
- Automatic programming.
- Computer learning.

Good introductions to Artificial Intelligence (AI) can be found in books by Barr and Feigenbaum [2], Charniak and Mc Dermott [7], Rich [22], Winston [25].

Expert Systems (ES) are computer systems designed with AI Techniques and capable of reasoning about knowledge in specific domains.

Distinguished features of ES are:

- Symbolic representation of knowledge.
- Symbolic inference.
- Heuristic search.

Knowledge is made of:

- Descriptions (sentences in a language)
- Relationship (dependencies and associations that could be: taxonomic, definitional, empirical)
- Procedures.

ES may incorporate special skill for:

- Increasing speed of program execution.
- Reducing errors.
- Increasing adaptability and robustness.

Motivations for building E.S. are:

- Dissemination of rare and costly expertise.
- Integration of diverse sources of knowledge.
- Effective and efficient use of the human expert for the following tasks:
  - Formalization and clarification of knowledge that results from having the human expert make his reasoning explicit.
  - Put the expertise in a form that will be reproducible and testable by many users.

A scheme for an ES architecture is shown in Fig. 1.

The user carries on a dialogue with the system through a **user interface**. Sophisticated interfaces may have natural language capabilities. Knowledge is stored in a **knowledge base** and is applied to facts stored into a Short Term Memory (STM) by an **inference mechanism** capable of using knowledge in a way that depends on the context stored in the STM. The STM contains what the computer currently believes. Knowledge is made of facts represented by **abstract expressions**, stored as data structures into **concrete representations**. The way the content of a representation is **indexed** is an issue of concrete representations.

Inference methods as well as permanent knowledge are stored into a Long Term Memory. Inferences are performed when facts are added or some requests arrive.

An ES has usually some **Explanation Facilities** as well as a **Knowledge Acquisition Facility** that interacts with an external domain expert or with a **Knowledge engineer** who helps the domain expert in expressing his knowledge in such a way that it can be processed by the system.

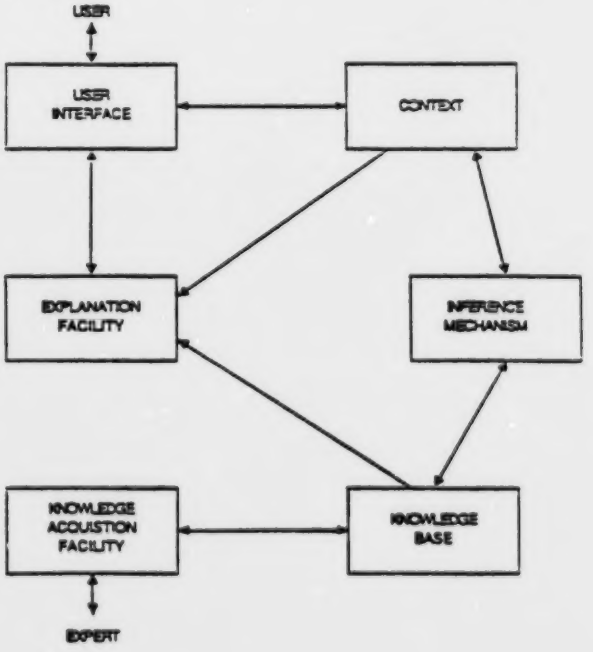

Figure 1: Schematics of a Complete KBES

Usually an Expert System is characterized by:
a Task, a Knowledge Representation Paradigm and a Control Structure characterized by one or more reasoning methods. There may be complications depending on how the knowledge was acquired, and how the system was evaluated.

Some typical **application areas** of ES, are listed in the following:

1. **Design**
   Task:
   A physical system to perform a specified function is designed.

   Examples:
   Design of structures, design of computers, design of simulators.

2. **Diagnosis**
   Task:
   Observations are interpreted to infer the state of a system.

   Examples:
   Possible causes of structural failure, diagnosis of machine faults.

3. **Interpretation**
   Task:
   Known data are analyzed to determine their meaning.

   Examples:
   Finite element analysis results, signal understanding, speech understanding.

4. **Monitoring**
   Task:
   Signals are continuously interpreted and alarms set if intervention needed.

   Examples:
   Signals from earth, patient after surgery, alarms in Electric Networks.

5. **Planning**
   Task:
   A program of actions to achieve certain goals is generated

   Examples:
   Construction planning, planning of lab. experiments.

Interesting books on Expert Systems are those by Harmon and King [12], Buchanan and Shortliffe [6], Hayes-Roth, Waterman and Lenat [13], Weiss and Kulikowski [23], Jackson [16].

2. REPRESENTATION OF KNOWLEDGE

Knowledge Representation (KR) in ES is a combination of:

- Data structures
- Interpretive procedures that if used in the right way in a program, will lead to knowledgeable behavior.

Kinds of Knowledge in KR are:

- Objects
- Events
- Time course of a sequence of events
- Cause-and effect-relations
- Performance (Knowledge of behavior)
- Meta-knowledge (Knowledge about what we know).

Cognitive tasks are:

- Acquiring more knowledge.
- Retrieving facts from the knowledge base relevant to the problem at hand.
- Formal reasoning (inference) about these facts in search of a solution.
- Procedural reasoning,
- Reasoning by analogy,
- Generalization and abstraction.
- Meta-level reasoning.

In order to have an explicit knowledge base, a system must rely on some well specified language (**knowledge representation language**) for encoding its belief.

A representation system must also provide access to facts **implicit** in the Knowledge Base (KB), by performing **inferences.**

Most of the power of knowledge based systems lies in the particular **domain knowledge.**

Powerful representation languages are logical languages with special features in the following aspects:

- Syntax
- Semantics
- Use.

It must be possible to interpret structures used in a KB system as **propositions** representing the overall knowledge of the system. Implicit in this constraint is that the structures have to be expressions in a language that has **a truth theory.**

The symbolic structures within a KB system must play **a causal role** in the behavior of the system that should agree with our understanding of them as propositions representing knowledge.

Unstructured knowledge representations are:

- **Predicate calculus and First Order Logic (FOL)** mostly used in general when knowledge is unstructured.

- **Production systems**, mostly used when:
  - Knowledge is diffuse.
  - Process can be represented by independent actions.
  - Knowledge can be separated from the manner in which it has to be used, or it has to model how a specific task is performed.
  - Reasoning about contexts, methods, goals.

- **Procedural languages** to be used when it is difficult to separate knowledge from its use.

Advantages of Knowledge Representation based on logic are that logic is:

- Precise
- Flexible
- Modular.

A disadvantage is the separation of knowledge representation and knowledge processing.

Deductive systems have to be:

- complete (a conclusion that can be reached is reached)
- consistent (deductions are always correct).

The service of a KR system is to determine if KB $\models \alpha$, meaning if α is implied in what is in KB.

This service depends only on the truth theory of the representation language.

Using First Order Logic (FOL) the service is theorem proving:

$$KB \models \alpha \text{ iff } \vdash (KB \supset \alpha).$$

That is, α is implied in what is in KB, if α is a theorem that can be proved based on the content of KB.

Unfortunately this decision problem is often unsolvable. This does not depend on the algorithms but on the problem itself.

Nevertheless, what is in KB can be limited so that tractable forms of inference can be performed.

Theorem proving is also made difficult by the fact that the main use of FOL is in the formalization of infinite collections of entities. On the contrary, in practical AI applications, the domains being characterized are usually finite and deal with incomplete Knowledge.

In order to circumvent theoretical difficulties, the inferential service provided by a KR system could be constrained to manage a limited form of retrieval inference leaving to user methods the responsibility of intelligently completing the inference. User methods may be based on forms of reasoning not necessarily grounded in a truth theory (see Levesque in [4]).

An interesting collection of papers on Knowledge Representation can be found in Brachman and Levesque [4].

2.1 Logic Languages for Knowledge Representation

2.1.1. Propositional Calculus used by (Sentential Logic) is based on relations represented by predicates and arguments.

Examples:
"Quebec IS A Province" is represented as:

PROVINCE (QUEBEC),

where PROVINCE is a predicate and QUEBEC is an argument.

A hierarchy (Taxonomy) can be built based on the IS A relation.

Some relations are expressed by predicates, some by functions. A function associates a unique object to a set of objects.

Example:
MARRIED [Father (Bill), Mother (Bill)]

A predicate can be TRUE or FALSE, a function returns an object. In the above example, MARRIED is a predicate, FATHER and MOTHER are functions.

To represent an English sentence we focus on the relations and entities that the sentence describes and represent them by predicates and functions.

The designer selects the alphabet of predicates and terms and defines the meaning of them (semantics of the representation language)

Elementary representations based on predicates are called literals.

A clause is a disjunction of literals.

Example:
"Ann is younger than Jane or Ann is younger than Mary" is represented by:

YOUNGERTHAN (Ann, Jane) $\vee$ YOUNGERTHAN (Ann, Mary).

Logic plays an essential role in drawing conclusions from premises. Conclusions and premises are logical expressions obtained by applying operators to literals and expressions. Logic operators are:

CONJUNCTION	(AND)
DISJUNCTION	(OR)
NEGATION	(NOT)
IMPLICATION	(IF-THEN).

Their definition is given by truth tables.

One of the most interesting theorems is the following.

Theorem: S1 or or S2 is equivalent to
If (not S1) then S2
that can be also represented as follows:
(~ S1 => S2).

The above theorem states that implication can be replaced by disjunction.

Laws and theorems allow to manipulate logic expressions.

Examples of Laws are:

DE MORGAN'S LAWS
DISTRIBUTIVE LAWS
COMMUTATIVE LAWS
ASSOCIATIVE LAWS
CONTRAPOSITIVE LAW.

Reasoning about expressions is based on rules of inference. An example of reasoning models is Modus Ponens.

Example:

Modus Ponens	W1	premise
	W1 => W2	implication rule
	W2	conclusion

=> represents implication.

An extensive presentation of Sentential Logic can be found in Klenk [17].

2.1.2. Predicate Calculus

Predicate calculus is a formalism able to

- Speak of objects
- Postulate relationships
- Generalize relationships.

STATEMENTS about individuals are PREDICATES. Arguments of predicates can be variables. A variable is a place holder that is to be filled by some constant.
An example of reasoning with variables is **universal specialization:**

	W1 (A)	premise
(∀ X)	[W1(X) => W2(X)]	implication rule
	W2(A)	conclusion

∀ X means "for every" object represented by the variable X.

Inference rules produce derived formulae called **theorems.**

The sequence of inference rule applications used in the derivation is a **proof.**

Some problem solving tasks can be regarded as finding a proof for a theorem.

Pieces of knowledge given to a reasoning program at the start of a problem solving activity are called **assumptions** or **axioms.**

Variables can be quantified according to the following examples.

Universal Quantifier

"All dolphins are grey"
(∀ X) Dolphins (X) => Color (X, Gray)

Existential Quantifier

"There is a person who wrote Hamlet"
∃ (X) WRITE (X, HAMLET)

The elements of Predicate calculus are:

Predicate Symbols
Function Symbols
Variable Symbols
Constant Symbols.

Terms can be composed with variable, constant and function symbols. **Atomic Formulae** are composed of predicate symbols and terms. **Atomic Formulae** are **Well Formed Formulae** (WFF). A **Formula Value** can be TRUE or FALSE. When **Logical Connectives** are applied to WFF, WFF are obtained.

An atomic formula or a negation of an atomic formula are **literals.** A **clause** is a disjunction of literals.

The **meaning** of a complex term or **formula** is function of the meanings of its parts (predicate Calculus has **compositioned semantics**).

An extensive presentation of the mathematical properties of Predicate Calculus, in view of the applications in Computer Science, can be found in Manna and Waldinger [18]. An introduction to automatic theorem proving with applications can be found in Wos, Overbeek, Lusk and Boyle [27]. The application of logical techniques to problem solving and other topics of AI is discussed in Nilsson [20].

Predicate calculus produces an **internal representation** that corresponds to a stylized version of the world.

Internal representations make the choice of referent explicit. (It may not be so in natural language sentences. In such a case we have a **referential ambiguity**).

If in natural language there is not a unique name for each individual entity, we **make up** names for each individual and we call them **tokens** or **instances.**

Example:
"John caught the train": if there are many individuals with the name John and many trains we will write:
caught(John-4,train-41).

An expression obtained by quantifying a WFF over a variable is also a WFF.

This version of the predicate calculus is called "**first order**" because it does not allow quantification over predicate symbols or function symbols.

A WFF can be given an **interpretation** by assigning a correspondence between the elements of the language and the relations, entities and functions in the domain of discourse.

2.2 Graphical Representation of Knowledge

Knowledge can be graphically represented by **semantic networks.** They are graphs consisting of:

- NODES representing objects, concepts, situations,
- LINKS expressing relations between them.

Nodes are either **constants** or **types.** Links are either labeled with an **attribute** or with the special label **is-a.**

This representation allows certain kinds of inference to be performed by simple **graph searching techniques.** A typical example consists in performing a **spreading activation search** beginning at two nodes between which a relation is looked for.

This activity is performed by **special matchers** that also allow to search for **inherited** properties through a chain of **is-a** links.

Special matchers can follow paths of other types of relations, exploit **bidirectional links** and use inherited properties only as **default assumption.**

More on this topic can be found in Nilsson [20], Charniak and Mc Dermott [7], Brachman and Levesque [4].

Example: 2.1

Let us represent a taxonomy about animals, insects and plants as shown in Fig. 2. In this particular graphical representation the nodes represent the elements of the taxonomy and the arcs are all of the same type, that is is-a. For example following the graph we can say that elephant is-a mammal, mammal is-a animal, animal is-a living entity and conclude that an elephant is-a living entity. This knowledge can be stored in a Knowledge Base by asserting a number of rules as follows:

Rules 2.1

(assert '(-> (inst ?x plant) (inst ?x life)))

(assert '(-> (inst ?x insect) (inst ?x life)))

(assert '(-> (inst ?x animal) (inst ?x life)))

(assert '(-> (inst ?x mammal) (inst ?x animal)))

(assert '(-> (inst ?x dog) (inst ?x mammal)))

(assert '(-> (inst ?x pig) (inst ?x mammal)))

(assert '(-> (inst ?x elephant) (inst ?x mammal)))

(assert '(-> (inst ?x bird) (inst ?x animal)))

(assert '(-> (inst ?x sparrow) (inst ?x bird)))

(assert '(-> (inst ?x eagle) (inst ?x bird)))

(assert '(-> (inst ?x roach) (inst ?x insect)))

(assert '(-> (inst ?x cockroach) (inst ?x roach)))

(assert '(-> (inst ?x flower) (inst ?x plant)))

For the sake of clarity, the variables are preceded by a "?".

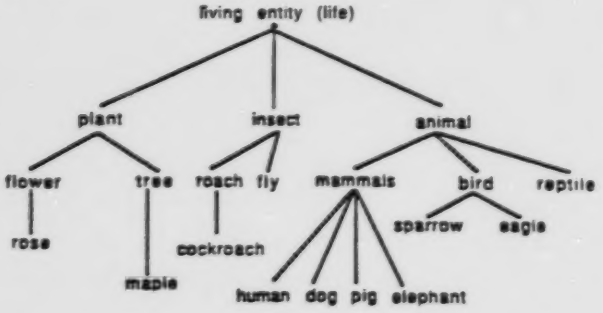

Figure 2 : Example of a Taxonomy

As all the rules are similar, we will explain them by considering one as a typical example:

(—(inst ?x mammal) (inst ?x animal)).

This expression is a representation (that can be easily manipulated by a computer program) of the logical expression

(∀ x) (inst (x, mammal) => inst (x, animal)).

That is "if x is a mammal then x is an animal" and this is true for every x.

Now that we have implication rules in the data base we can add facts like:

(inst Fido dog)

that is (Fido is a dog).

We would like to provide a reasoning component capable of performing inferences and answering a question like:

"is Fido an animal?"

This can be done by attempting to retrieve an information that is not explicitly in the KB but that can be inferred from the KB content. We could introduce a command like:

(retrieve '(inst Fido animal)).

Based on this request, the system can consider (inst Fido animal) as a theorem to be proved and the proof as a goal to be achieved. It can attempt to match the goal with a conclusion of a rule. There is a rule:

(—(inst ?x mammal) (inst ?x animal))

whose conclusion matches with the goal if we assume that the variable ?x takes value Fido. This binding is legal because ?x is a variable that can assume any value.

As a result of this operation we have now another goal, namely:

(inst (?x=Fido) mammal),
which matches the rule:
(—(inst ?x dog) (inst ?x mammal))
which generates another goal:
(inst (?x=Fido) dog)
that matches with the fact (inst Fido dog).

So, what we wanted to retrieve can be inferred from facts and rules in the KB, thus it is implicitly there. The Expert System that performed the "backward chaining" shown before would answer "yes" to our question. Now we would like it to tell us "why" the answer was yes and to provide a chain of explanations. Explanation facilities can produce something like:

"I know that:
(—(inst ?x dog) (inst ?x mammal))
by binding ?x to Fido, I can conclude (inst Fido mammal).
I know that:
(—(inst ?x mammal) (inst ?x animal))
by putting ?x = Fido, I can conclude
(inst Fido animal)."

Another interesting aspect of a Taxonomy represented as shown above is that properties can be inherited through links. The example of Fig.3 shows how nodes in the hierarchy can be associated attributes. The is-a hierarchy allows one to inherit attributes and to asses that Dumbo breathes without specifying this property for each elephant.

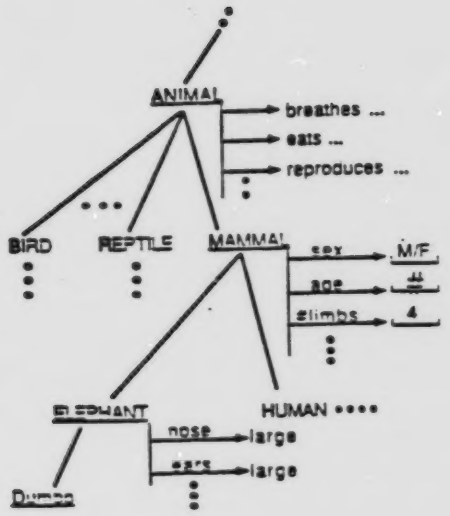

Figure 3 : Frames for "Innerntance Hierarchies"

2.3 Structured Object Representation

The appropriateness of a representation depends on the application. Efficient storage retrieval and modification are key concerns in selecting an implementation design.

Several related predicate calculus expressions can be grouped into larger structures (units) that are identified with important objects in the subject domain of the system. When information about one of these objects is needed by the system, the appropriate unit is accessed and all of the relevant facts about the object are retrieved at once.

A representational scheme in which the facts are indexed by terms denoting entities of objects of the domain is called an **object centered representation.**

There are some advantages in converting to a representation that uses events and binary relations. Primary advantage is modularity. Additional information can easily be incorporated by adding new binary relations, functions and associated rules. These information structures are called **frames.**

The advantages of frame languages are considerable. They capture the way experts typically think about much of their knowledge, provide a concise structural representation of useful relations, and support a concise definition-by-specialization technique that is easy for most domain experts to use.

In addition to encoding and storing beliefs about a problem domain, a representation facility typically performs a set of inferences that extends the explicitly held set of beliefs to a larger, virtual set of beliefs. Thus, the representation facility participates in the system's reasoning activities by providing these "automatic" inferences as part of each assertion and retrieval operation. Frame languages are particularly powerful in this regard because the taxonomic relationships among frames enable descriptive information to be shared among multiple frames (via inheritance) and because the internal structure of frames enables semantic integrity constraints to be automatically maintained.

Fig. 4 shows the Predicate Calculus representation of a set of relations that could be graphically represented by a semantic network having predicate names as link labels and arguments as nodes.

One way of associating domain-dependent behavior with frames is by attaching to them in various ways procedures written in the underlying programming language (e.g., LISP, KL-ONE and KRL; see Winston and Horn [25] or Wilensky [24] for more detail on LISP, Brachman and Levesque [4] for an introduction to KL-ONE and KRL). Additional facilities can declaratively describe domain-dependent inference rules, analysis decision rules, actions that can be taken in the domain by various agents, simulations of object behavior.

Frames are also related to Semantic Networks. NODES and LINKS of a network can be structured into FRAMES. Network partitioning into higher level units like scenarios or depictions is an important problem as well as the one of choosing semantic primitives.

Fig. 4 shows three frames that can be used for representing arguments of relations. Properties can be added to each frame and inherited through a hierarchy.

PREDICATE CALCULUS REPRESENTATION OF A SET OF RELATIONS

```
isa ( Clyde, Robin )
isa ( Robin, Bird )
has-part ( Bird, Wings )
```

FRAME REPRESENTAION

```
( Clyde                          ( Robin
        ( isa Robin )                    ( isa Bird
                .                                .
                .                                .
                .                                .
        ( properties )                   ( properties )
                .                                .
                .                                .
                .                                .
)                                )

( Bird
        ( isa animal )
        ( has-part wings )
                .
                .
                .
)
```

Figure 4 : Frame Representation

Frames can also be used to represent expectations about objects and sequence of events built from previous experience. A frame may contain procedural advice to the matcher that compares it with the data. Frames are examples of structured knowledge representations belonging to a class of data structures called schemas. Schemas refer to the organization of past experiences which must always be supposed to be operating in any well adapted organic response. Types of schemas according to Rich [22] are:

Frames, used to describe properties of objects or expectations often from different points of view.

Scripts, used to describe common sequences of events.

Stereotypes, used to describe cluster of characteristics found in a class of individuals.

Rule models, used to describe common features shared among a set of rules.

2.4 Knowledge Representation Implementation

Different formalisms can be coded in different programming languages.

The most popular Expert System shells are written in C, LISP or PROLOG. PROLOG is a language conceived for Logic Programming, although now it has been shown how object centered representations can be implemented in PROLOG. A good introduction to PROLOG and its applications to AI can be found in Bratko [5].

The following parameters can be used for the choice of the language in implementing the required representation methods:

- •Programming time
- •Execution time
- •Modularity
- •Maintainability
- •Understandability

Choice of knowledge representation formalism depends of the following aspects:

- •Representational adequacy
- •Inferential adequacy
- •Acquisitional efficiency.

A recent discussion on AI programming methods can be found in Bobrow et al. [3] and on a special issue of the Communications of the ACM [8]. Architectures for Artificial Intelligence are reviewed in a recent special issue of the Computer Magazine [14].

3. PROBLEM SOLVING

The following are the most popular problem-solving strategies:

- • Rule Based Deduction (Forward Chaining, Backward Chaining)
- • Means-Ends Analysis
- • Problem Reduction
- • Plan-Generate-Test
- • Backtracking
- • Hierarchical Planning
- • Constraint Handling
- • Agenda Control.

3.1 Rule-Based Deduction Systems

Deduction systems are based on rules of the type:
if precondition **then** conclusion or action.

A **precondition** is a logical expression of predicates.

EXAMPLE 3.1.1.
We have the following rule:

All married men have a wife:
$(\forall X)$ MARRIED(X) — HASWIFE (X).

If we know that all variables are universally quantified, we can avoid writing the universal quantifier:

MARRIED (X) — HASWIFE (X).

Using truth-tables we can prove:

~MARRIED (X) $\vee$ HASWIFE (X).

We have the following fact:

Henry is married: MARRIED (Henry).

We can reason as follows:

As the rule is true for every value of X, it is true for X = Henry:

MARRIED (HENRY) $\wedge$ (~ MARRIED(HENRY) $\vee$ HASWIFE(HENRY)) —
MARRIED (HENRY) $\wedge$ HASWIFE(HENRY).

HASWIFE(HENRY) is a new conclusion to be added to the data-base.
EXAMPLE 3.1.2.

1) Father and Son have the same last name:
~SON (X,Y) $\vee$ SAMELAST (X,Y)

2) Harry is the son of George:
SON (Harry, George)

3) Conclusion: SAMELAST(Harry, George)

This type of reasoning produces a **Unit Clause** containing exactly one literal and is called **Unit-Resulting Resolution.**

The Matching Process that produces the following variable binding:
Harry / X George / Y
Is called **unification.**

More formally:

Unification is finding substitutions of terms for variables to make expressions identical.

If a variable X is assigned a constant value A then X is **bound** to A

Resolution is an inference procedure used in a theorem proving system. It tries to infer a new clause called **Resolvent** from two **Parent Clauses.**

The resolvent is computed by taking the disjunction of the two clauses and then eliminating the complementary pair.

Reasoning can be based on the following theorem proving scheme:

S is a set of WFF
W is the goal WFF.

we wish to prove W from S.

Proof can be carried out by considering that if W logically follows from S then none of the interpretations satisfying S can satisfy ~ W, the set S v {~W} is unsatisfiable. In practice, the system Knowledge Base contains a set of clauses, and a Binary Resolution Scheme is applied to pair of clauses to produce a new clause. This is accomplished by building a refutation tree. Termination condition is the deduction of the empty clause from the set of facts and the negation of the proof.

It is impossible to have a general method to decide the validity of quantified expressions. An expression is valid if its value is true for all possible assignments to its variables.

If an expression is valid then there is a procedure for deciding its validity. This is no longer true if the expression is not valid.

The Most Popular Strategies for Producing Resolution Refutation are:

1) **Breadth-First**
The i-th level resolvent is one whose deepest parent is an (i-1)-th level resolvent. This strategy is complete but inefficient. Complete means that the strategy will find a contradiction (eventually) whenever one exists. but it may vary without stopping if a contradiction does not exist.

2) **Set-Of-Support**
At least one parent of each resolvent is selected among the clauses resulting from the negation of the goal WFF or from their descendants (the set of support.) This strategy is complete and more efficient than breadth first.

3) **The Unit-Preference Strategy**
A single literal clause (unit) is selected to be a parent in a set-of-support strategy resolution.

4) **The Linear-Input Form Strategy**
Each resolvent has at least one parent belonging to the base set (axioms and goal negation). This strategy is incomplete but simple.

5) **Ancestry-Filtered Form Strategy**
Each resolvent has a parent that is either in the base set or that is an ancestor of the other parent. This strategy is complete and efficient.

Answer Extraction involves converting a refutation tree to a prooftree. The operation involves converting every clause arising from the negation of the goal WFF into a tautology. The converted proof tree is a resolution proof that the statement at the root logically follows from the axioms and tautologies.

More details on resolution strategies and answer extraction can be found in Nilsson [20].

Resolution strategies based on a systematic search for a solution may be inefficient. For this reason, other reasoning strategies have been proposed. They won't be discussed here. but a reference for the most popular of them will be given in the following.

Forward and backward chaining strategies won't be discussed here for the sake of brevity. An extensive presentation of these can be found in Nilsson [20].

Detailed descriptions and applications of agenda control strategies can be found in Hayes-Roth et al. [13] and in Buchanan and Shortliffe [6].

Simple and effective introductions to planning can be found in Nilsson [20] and Rich [22].

Other Strategies are Conceived for Reasoning with Semantic Networks.

Reasoning with semantic networks is based on matching network structures.

A network fragment is constructed. representing a query and then matched using graphical methods against the network data-base.

Variable nodes are bound in the matching process to the values they must have to make the match perfect.

The Matcher can make Inferences during the matching process. The Matcher can be rule-based. has to take into account link types and can create a network structure that is not explicitly present in the network.

Further discussion on these topics can be found in Nilsson [20], Barr and Feigenbaum [2], Brachman and Levesque [4].

It is also possible to integrate declarative and procedural knowledge. The method for such an integration is the following.

Represent declarative knowledge encoded in logic expressions along with heuristic instruction for its use. An example could be specifying what knowledge will be relevant to achieve a specific goal. A goal can be represented by a list like:
(goal animals (try-using theorem 1 theorem 2)).

Several classes of theorems can be suggested by the use of filters as in the following example:
(goal fish (filter about bioiogy)).

Another possibility is to perform default reasoning, like in the following example:
(unless fish (x) assume flies (x))

These extended inference modes may violate the property of monotonicity, making it possible that something that is supposed true in a certain phase of reasoning may result faise in a subsequent phase.

In general, reasoning strategies can be based on meta-knowledge that decides how to partition a problem into subproblems and when subgoals. set for solving subproblems. can be made active.

There may be several levels of control meta-knowledge representing models of human problem solving in specific domains. Interesting theoretical considerations on these problems can be found in Brachman and Levesque [4]. Practical considerations can be found in Hayes-Roth et al. [13].

Reasoning can be based on imprecise knowledge implying algorithms for measuring and combining degrees of imprecision. An important component of this topic is probabilistic reasoning. Theories for imprecise reasoning are described in a book by Pearl [21]. An example of the use of fuzzy logic with a frame-based system can be found in De Mori [10].

Knowledge acquisition is an important issue in Expert Systems. Usually it is carried out by the Knowledge Engineer who is familiar with the representation and reasoning facilities of the available software and the Domain Expert. Hayes-Roth et al. [13] discuss the problem of

interactive Knowledge acquisition.

Important efforts have been done in the recent years in Automatic Learning (see Michalski et al. [10]). Although interesting results have been achieved, very little on Machine Learning is available in commercial products.

Another important feature of Expert Systems is the capability of interacting with casual users. A number of commercial products for Natural Language Processing are now available, and better ones are expected to come in the near future. An introductory book by Dee Harris [9] contains a simple review of methods and systems. Voice input-output may also become a possibility for the future. A review of problems and solutions can be found in De Mori [10].

Interfacing Expert Systems with Data-Bases, numerical packages, Computer Aided Design packages other programs and environments is an extremely important practical issue that is receiving more and more attention from Software Engineers.

4. APPLICATIONS

A number of practical Expert Systems has been developed in the recent years. Reference [11] lists more than 130 Expert Systems in use: most of them are for sale.

These Expert Systems are applied in various Engineering, Financial and Legal domains and are implemented in various languages. Reference [11] contains also an overview of Expert System building tools.

References [1] and [15] report interesting applications related to Computer Aided Manufacturing.

Reference [26] contains a critical review of ES technology: Refs. [20] and [30] discuss interesting applications.

An intensive teaching activity for Expert Systems is going on in Canada. Students at McGill University, as well as in other places, develop basic KR and reasoning tools in course projects. In the last years they have also developed Expert Systems projects in various Engineering areas.

ACKNOWLEDGEMENTS

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BIBLIOGRAPHY

[1] Artificial Intelligence Magazine, vol. 7, no. 4, Fall 1986.

[2] A. Barr and E.A. Feigenbaum, Editors, The Handbook of Artificial Intelligence, vol. I, II, III., W. Kaufmann publ., Los Altos, CA., 1981.

[3] D.G. Bobrow, U.M. Kahn, M.J. Stefrik, Integrating Access-Oriented Programming into a Multiparadigm environment., Software Magazine, vol. 3, no. 1, Jan. 1986.

[4] R.J. Brachman and H.J. Levesque, Eds., Readings in Knowledge Representation., W. Kaufmann publ., Los Altos, CA., 1985.

[5] I. Bratko, PROLOG Programming for Artificial Intelligence, Addison-Wesley publ., Reading, MASS., Reprint 1985.

[6] B.G. Buchanan and E.H. Shortliffe, Rule-Based Expert Systems., Addison-Wesley publ., Reading, MASS., Reprint 1985.

[7] E. Charniak and D.V. Mc Dermott, Introduction to Artificial Intelligence, Addison-Wesley publ., Reading, MASS., 1985.

[8] Communications of the ACM, vol. 28, no. 9, Sept. 1985.

[9] M. Dee Harris, Introduction to Natural Language Processing., Reston publ., A Prentice-Hall co., Reston, VA., 1985.

[10] R. De Mori, Computer Models of Speech Using Fuzzy Algorithms., Plenum publ., New York, N.Y., 1983.

[11] Expert Systems Strategies, vol. 1, no 8, August 1986.

[12] P. Harmon and D. King, Expert Systems, John Wiley, New York, N.Y., 1983.

[13] F. Hayes-Roth, D.A. Waterman and D.B. Lenat Eds., Building Expert Systems Addison-Wesley publ., Reading, MASS., 1983.

[14] IEEE Computer Magazine, vol. 20, no. 2, Feb. 1987.

[15] IEEE Transactions on Pattern Analysis and Machine Intelligence, vol. PAMI 7, Sept. 1985.

[16] P. Jackson, Introduction to Expert Systems, Addison-Wesley, Reading, MASS., 1986.

[17] V. Klenk, Understanding Symbolic Logic, Prentice Hall, Englewood Cliffs, N.J., 1983.

[18] Z. Manna and R. Waldinger, The Logic Basis for Computer Programming, Addison-Wesley, Reading, Man., 1985.

[19] R.S. Michalski. J.G. Carbonell. T.M., Mitchell Eds., Machine Learning, vol. I, II, Tioga publ., co. Palo Alto, CA., 1983.

[20] N.J. Nilsson. Principles of Artificial Intelligence. Tioga publ. co., Palo Alto. CA., 1980.

[21] J. Pearl. Heuristics. Addison-Wesley publ., Reading, MASS., 1984.

[22] E. Rich. Artificial Intelligence. Mc Graw Hill. New York, N.Y., 1983.

[23] S.M. Weiss and C.A. Kulikowski. A Practical Guide to Designing Expert Systems. Rowman and Allanheld publ., Totowa. N.J., 1984.

[24] R. Wilensky. LISPcraft. Norton. 1984.

[25] P.H. Winston. Artificial Intelligence. Addison-Wesley publ., Reading, MASS., 1977.

[26] P.H. Winston and B.P.K. Horn. LISP. Addison-Wesley publ., Reading. MASS., 1981.

[27] L. Wos. R. Overbeek. E. Lusk and J. Boyle. Automated Reasoning: Introduction and Application. Prentice Hall publ., Englewood Cliffs. N.J., 1984.

[28] D.G. Bobrow. S. Mittal and M.J. Stefik. Expert Systems: Perils and Promise. Communications of the ACM, vol. 29. no. 9. pp. 880-894. 1986.

[29] IEEE Software Magazine. vol. 3. no. 2. March 1986.

[30] IEEE Computer Magazine. vol. 19. no. 7. July 1986.

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Automation

by

E. Wintergrass

Digital Equipment Corporation

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S E S S I O N 2

CIMP and Advanced Materials / SIMM et les matériaux avancés

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Manager,
Manufacturing Technology,
Noranda Research Centre

directeur,
technologies de fabrication,
Centre de recherche Noranda

DESIGN ISSUES FOR COMPUTER-INTEGRATED MATERIALS PROCESSING

BY
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The University of Delaware

Introduction

Design teams of the future need participants from manufacturing, tooling, marketing, and maintenance and well as from the traditional areas. Such a design team will implement its design with Computer-Integrated Materials Processing. Even now, the design and manufacture of composite structures is hindered without such integration.

In composites, the design cannot be done without choosing a manufacturing process and a tooling approach. This coupling requires a level of integration and cooperation seldom achieved previously in the traditional approach to mass production.

The composites designer has many more options at his disposal than the traditional designer of isotropic material structures. They can be beneficial or burdensome, depending on how well the design process is supported with experience and a data base. First-order options include the selection of fiber and matrix materials.

Fiber materials include carbon, glass, aramid, boron, silicon carbide, polypropylene, and other natural and synthetic fibers. They are chosen principally for their stiffness properties, although strength, environmental resistance, and cost sometimes dictate the choice.

Matrix materials include thermosetting or thermoplastic polymers, metals, or ceramics. They are chosen for environmental resistance, cost and processability.

Integration of Manufacturing and Design

Any manufacturing process can be divided into a series of unit operations. These unit operations encompass each task involved in producing and moving materials through to a finished, tested, and delivered product.

There are several common routes for manufacturing composite structures. The unit operations involved fall into common categories (Figure 1). The two most critical categories are the primary material form and the primary shapemaking process. The various material forms are applicable to differing sets of shapemaking processes, and to the requirements of different projects. Sometimes it makes sense to use sheets of fibers that have been preimpregnated with polymer resin (prepreg). Other times it may be more economical to combine dry fibers with a polymer (or other matrix) directly into the final shape. Project economics and feasibility requirements dictate that the design team must select the primary material form(s) and the primary shapemaking process(es) as part of the preliminary design process.

In the past, a designer's job was to define the shape of the final product. In composites, he also has to define the amount and orientation of the reinforcement that controls the internal microstructure. The microstructure interacts strongly with the external shape, producing another type of coupling to deal with. Certain composites manufacturing processes, such as injection molding, are capable of producing almost any shape. However, this shape flexibility is traded off at the expense of a lack of control over microstructure and thus properties. Other processes, such as filament winding, permit wide control of variation in fiber orientations and thus allow tailorability of properties, but at the expense of the ability to form certain shapes. The design team must simultaneously define a shape, a microstructure (reinforcement scheme or fiber orientations), and a manufacturing process that is capable of producing it (Figure 2). There may be more than

one way to create the same shape and microstructure. The decision of which to use will be based on life cycle costs.

It's easy to see that the options available to the composites designer can be overwhelming. He needs the best computer tools to help him do his job.

Tools for the Design Team

Our job in composites research sometimes seems like a mission to produce and assemble tools for design, analysis, testing, and manufacturing of composite structures.

Many people have devoted themselves to producing computerized tools for composites. Almost invariably, they have been aimed at the needs of specialists, to help them do their traditional job. Codes are available for lamination theory stress analysis, thermal analysis, flow modeling, test data reduction, etc.

We strongly believe that computerized tools are needed for the generalists, such as the project managers, directors, and vice presidents, who, like designers, have to make broad compromises to achieve overall project goals. We want to aid in the early decisions such as materials selection and manufacturing process selection, and in the integration of all the decisions in the design process.

One great benefit to be derived from such an integrated tool is a better feel for which design decisions can be made analytically, and which ones are simply based on experience or experiment. The reliability of the information in each part can be assessed, and the sensitivity of the answers to small changes in any of the input parameters can be determined.

From the research viewpoint, such an assessment can readily be employed to drive the research agenda. Consequently, researchers can be certain that they are working the most high-leverage issues available to them.

Most of us think of computer tools as analysis codes. Now we can expand that traditional role for computers. Data bases are also important computerized tools that can help the engineer by making quantitative experience available to him when he needs it. Even qualitative experience can be made available through knowledge-based systems. These rules of thumb can be used to link analytical methods. Another important role is to help define experimental programs to gather information that are beyond the capability of analysis to predict, that don't reside in the existing data base, or that go outside the available heuristics.

The use of expert systems has another great benefit. It permits the inclusion of manufacturing and maintainability issues at the very beginning of the design process. This philosophy is called "Unified Life-Cycle Engineering". It creates a complete set of computerized information that can be accessed at any time during the life cycle of the product.

The decisions made in the very early stages of a new product design can dominate all aspects of product development for years. It has been estimated that 70% of the cost of a project is determined in the conceptual design phase (Figure 3). The selection of a composites concept in the first place (as opposed to a more traditional material system) is often made on the basis of very little information. The following decisions, those of materials of construction and manufacturing processes, are also critical decisions that are typically made with too little information and in a nontraceable, seat-of-the-pants manner. Many times all of the alternatives are not even considered. Once materials and processes have been chosen in a quantifiable and traceable way, design within the context of the specific process can begin (Figure 4). The research groups at CCM involved in the various manufacturing processes have as their long-term goal the creation of integrated systems specific to their process.

CCM Research

All of our research relates to design in one way or another. We want to be able to categorize all of our research in terms of its relation to the overall design process. As an emerging technology, composites is struggling with the change from labor-intensive hand processes to either continuous processes or to batch operations that are fast and repeatable. We have focused on manufacturing as the area in which we can make the best change in a poorly understood environment. Composites research has focused on technology generation, and with good reason. But there is a need for more emphasis on system design, if composites are to find ever increasing fields of application. In order to better respond to our customers in industry, academia, and government, we must emphasize the system design aspects of composites as well as technology generation.

At CCM, for the reasons discussed above, much of our research is devoted to either primary materials fabrication or primary shapemaking processes. Some of these processes are widely used in commercial applications. Others are just beginning to emerge from the research laboratories to the prototype stage. Still others remain in the very early conceptual phase.

We are involved in those processes with the most potential for improving composites position in the materials marketplace, such as robotic fiber placement, thermoplastic sheetforming, textile preforming, and liquid molding.

Summary and Conclusions

Computer-Integrated Materials Processing is one of our important goals. However, its promise will not be fulfilled without equal attention to the integration of the design process that must precede materials processing. The design team of the future will not survive with anything less.

Dick J. Wilkins

Dr. Wilkins, Professor of Mechanical Engineering, is the Director of the Composites Center at the University of Delaware. The Center encompasses the Center for Composite Materials (founded in 1974), the National Engineering Research Center for Composites Manufacturing Science and Engineering (founded in 1985), and the U. S. Army Center of Excellence for Manufacturing Science, Reliability, and Maintainability Technology (founded in 1986). He received his Ph.D. in Aerospace Engineering from the University of Oklahoma in 1969. Until 1 January 1986, he had spent 17 years with the Fort Worth Division of General Dynamics, where he was responsible for numerous technology development activities in composites, including the U. S. Air Force structural certification of the first production graphite-epoxy structures, the empennage of the F-16 aircraft.

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COMPOSITES UNIT OPERATION CATEGORIES

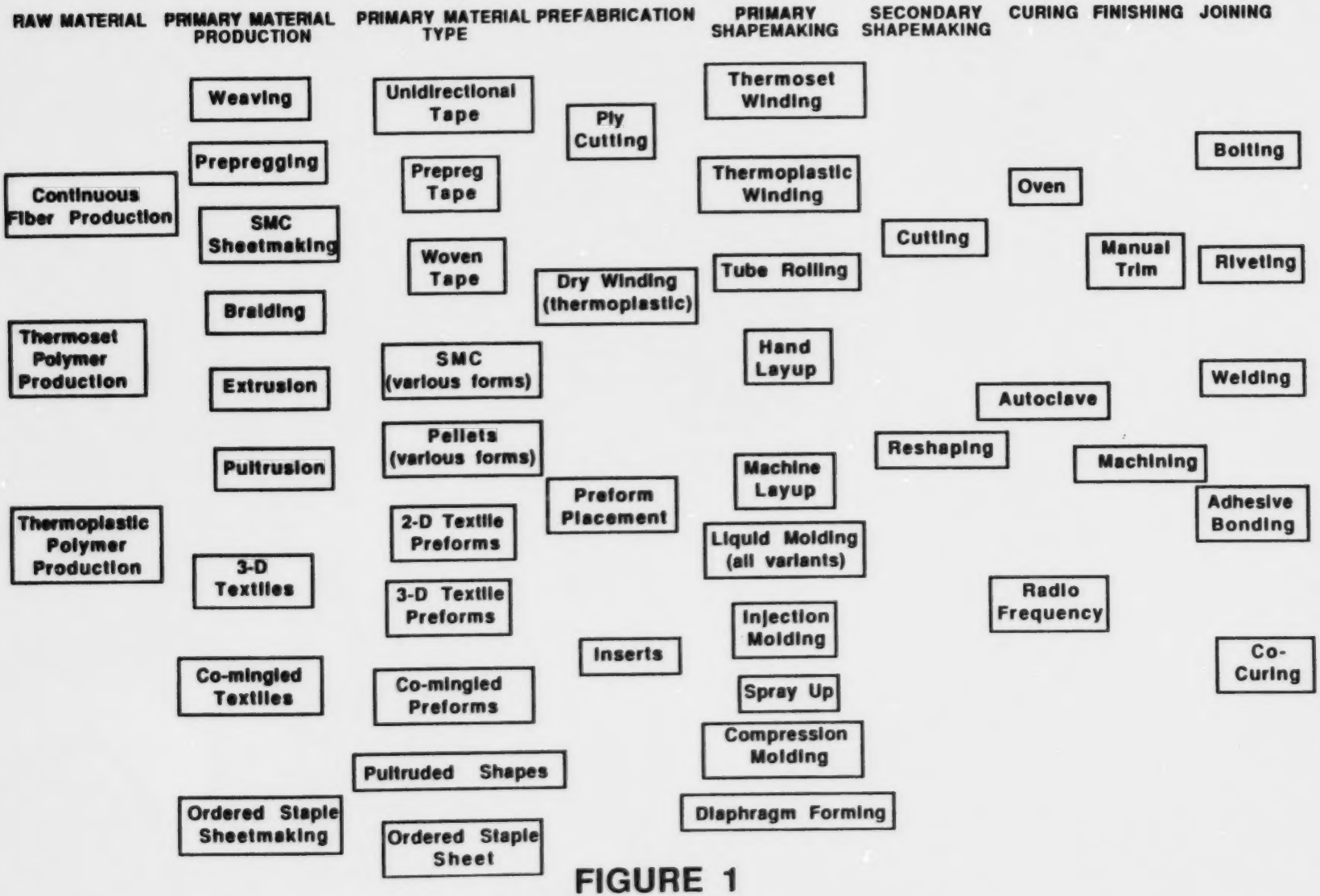

FIGURE 1

INTERACTION AMONG MANUFACTURING, MATERIALS, AND CONFIGURATION

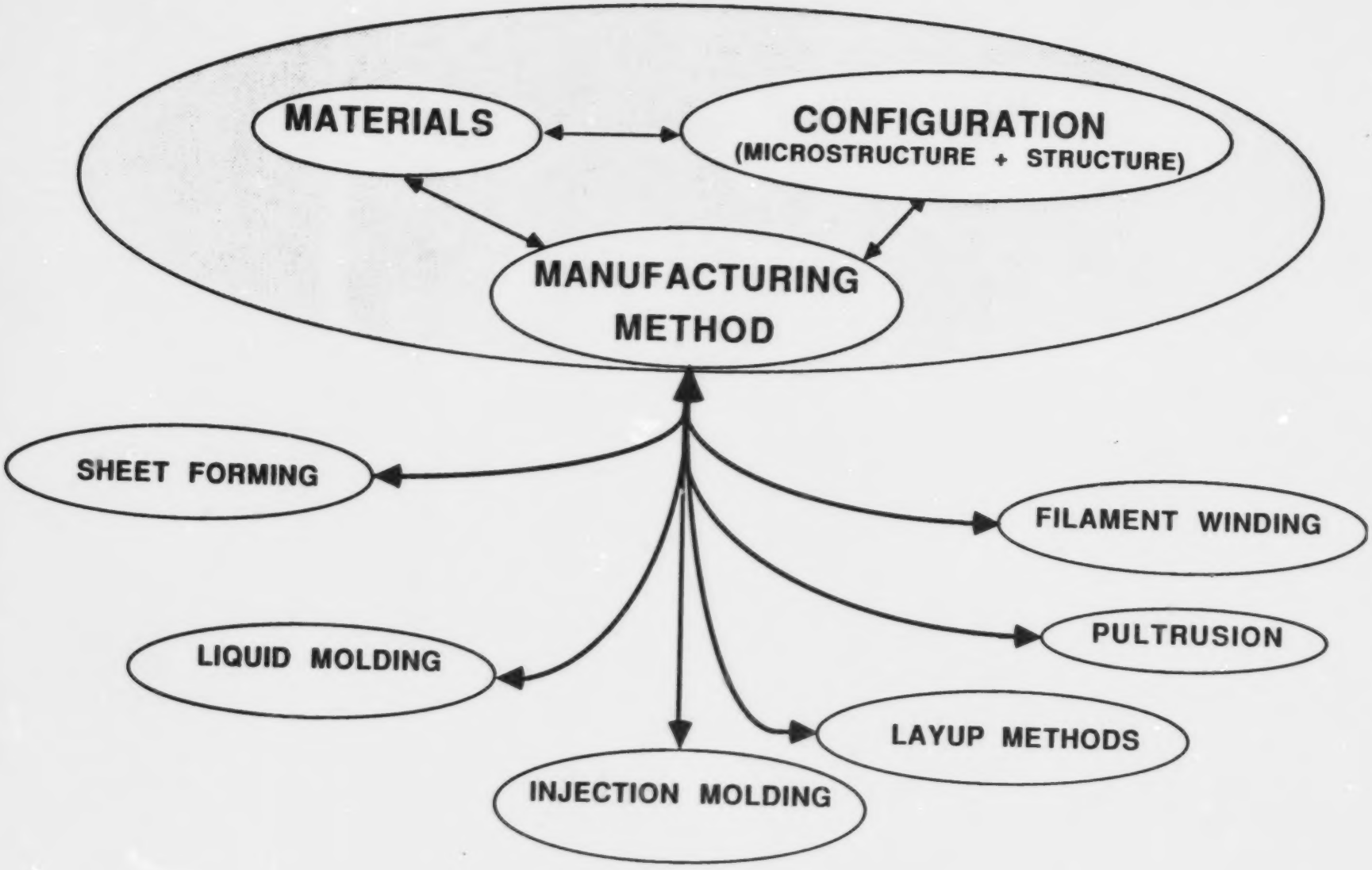

FIGURE 2

WHY EARLY DESIGN DECISIONS ARE CRITICAL

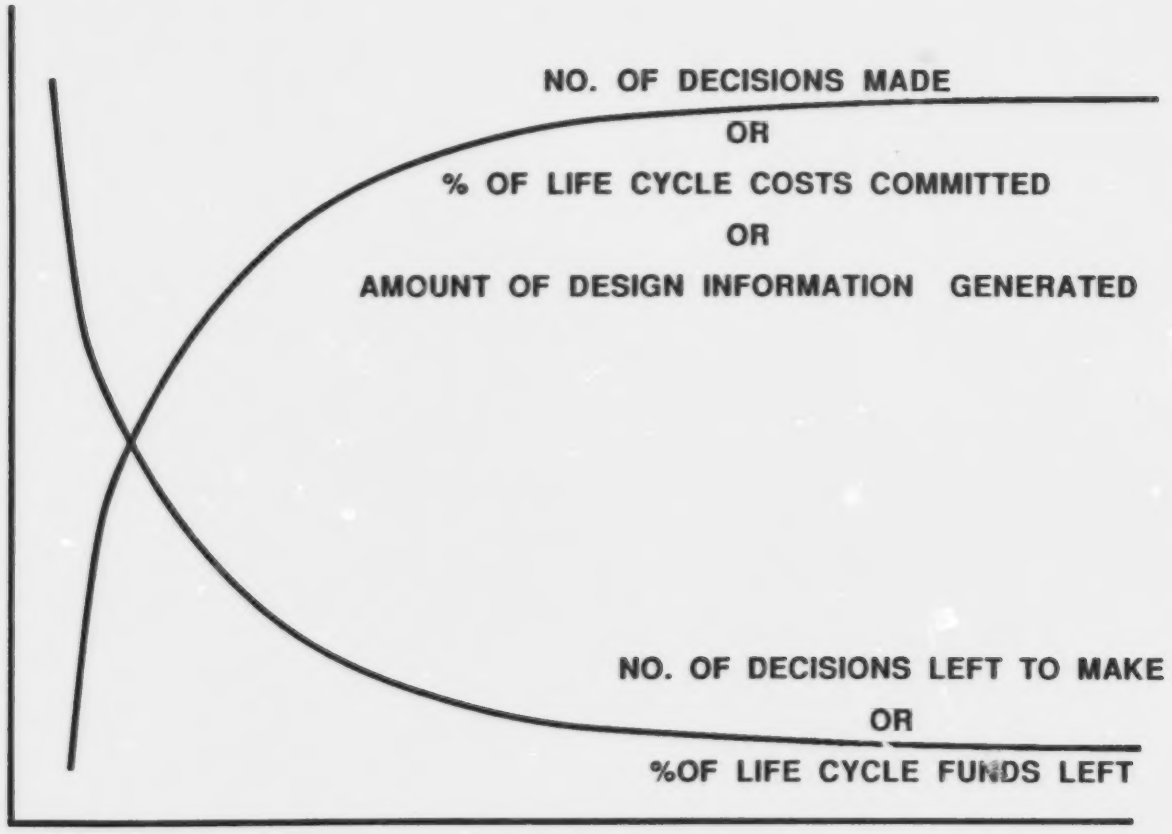

FIGURE 3

INTEGRATED DESIGN WITHIN ONE PROCESS

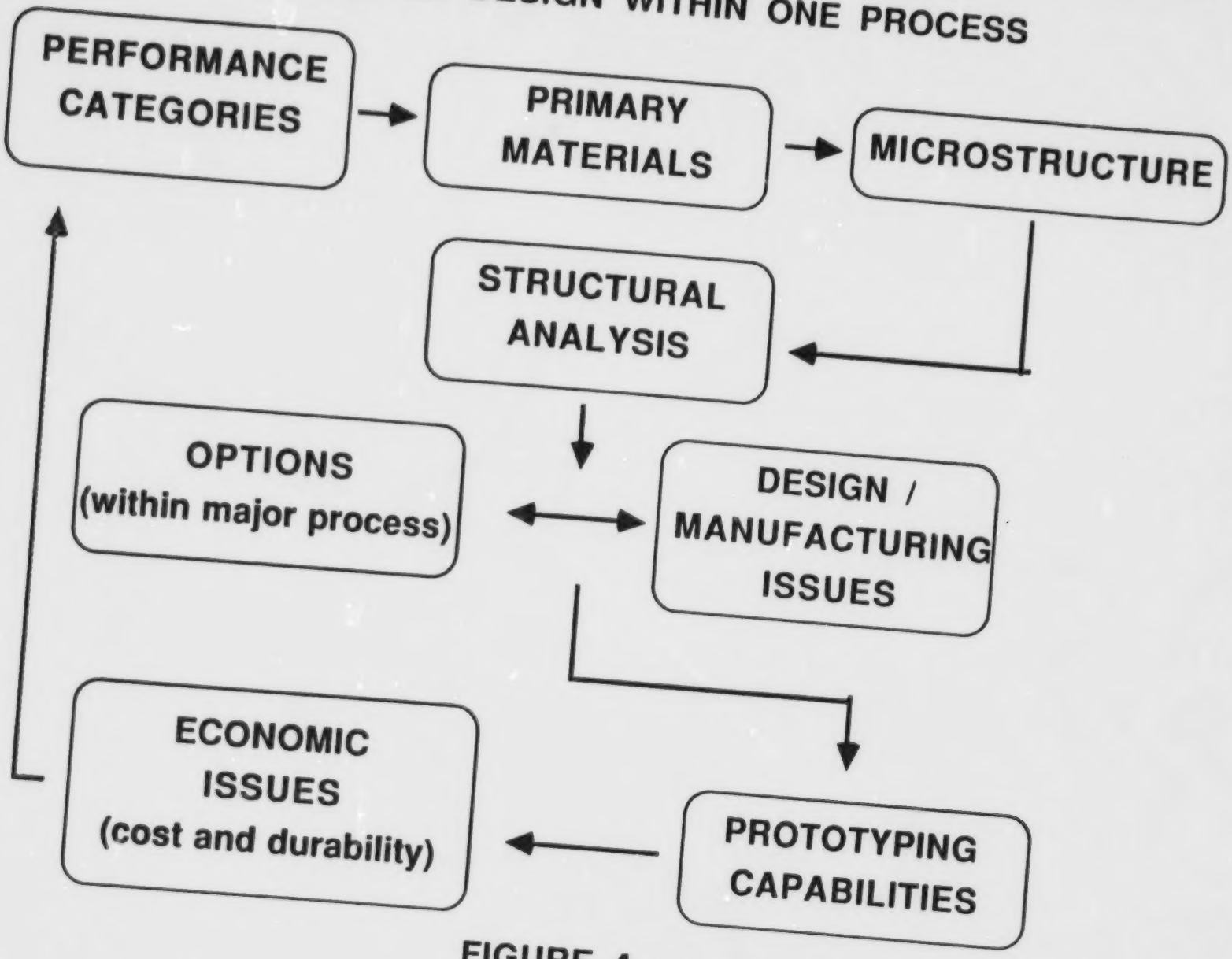

FIGURE 4

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Plastics, Rubbers and Composites

by

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ZA ALLOYS - THE DEVELOPMENT OF A DATA BASE AND SOFTWARE FOR GRAVITY CASTING AND BEARING DESIGN

by

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ZA (Zinc-Aluminum) alloys are a class of high strength foundry alloys which were developed in large part by Noranda Research (now Technology) Centre within the last 10-15 years. As alloy systems go, this makes the ZA alloys a recent fledgling in comparison to the well established alloy systems, such as aluminum and bronze alloys, which have many decades of development behind them.

The ZA family of alloys presently encompasses three alloys, namely ZA-8, ZA-12 and ZA-27, the numerical codes designating the approximate aluminum content in wt%. Earlier zinc alloys, particularly No's 2, 3 and 5, are still extremely popular, but which lack the competitiveness and technological edge required of today's advanced materials. The ZA family is an expanding one and new alloys are being developed as the performance requirements of castings continue to rise.

The needs of the designer, foundryman and end user are rapidly changing and with this has come the need for computer integrated materials processing (CIMP) from alloy preparation through to a near net or net shape end product, not only in advanced materials but in traditional foundry alloys too.

At Noranda, we are continuing to promulgate the data base necessary to provide designers and foundrymen with the tools they need to use ZA advanced alloys successfully. In particular, this has been, and is still being, done through property development, establishment of foundry parameters, both for pressure die casting and gravity casting, process simulation and bearing design. These data were and are being generated in such a way as to enable user friendly software to be developed and used in the industry.

In this paper the development of a data base for ZA alloys in the areas of casting and bearings will be described, including its relevance to PC compatible computer software for risering and gating of gravity castings, and in the design of continuous rotation journal bearings.

***

SESSION 3

CIMP and Process Simulation / SIMM et la simulation des procédés

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MOULDING PROCESSES

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1. INTRODUCTION [1,2]

Plastics processing generally involves the transformation of a solid resin, usually in the shape of pellets or powder, unreinforced or reinforced with glass, carbon or mineral fibers, into a final product with a specific shape, dimensions and properties. This trans-formation may be viewed as a multi-step process involving : solids transport, heating, melting, mixing, melt conveying, shaping, cooling or curing, and finishing.

Plastics processing operations can be classified into two general categories as follows :

a) Primary Forming Processes
b) Secondary Forming Processes

The primary forming processes can be in turn be subdivided according to the dimensional control of the shaping step.

Two dimensional operations include sheet, pipe and profile extrusion, film blowing, fiber spinning, wire coating, calendering, etc. These processes are generally continuous operations.

Three dimensional operations include compression, injection and blow moulding. These processes in most cases are intermittent or cyclic operations.

The secondary forming processes involve the treating of a product previously formed in a primary process in order to further change its shape, appearance or improve its properties. Among these operations we can cite : thermoforming, embossing, hot/cold rolling, ultrasonic welding, plating and decorating.

The processing of plastic materials is characterized by complex interactions between the material (resin,fibers), equipment configuration(i.e. mould and die design), and processing conditions. These interactions ultimately determine the mouldability of the material,the economics of the process and the properties of the final product.It is therefore essential to develop a unified approach which incorporates models for the material behaviour, the polymer processing operation and product performance. This " integrated " approach is the core to the advancement of the " Computer Integrated Materials Processing - CIMP " research and development strategy.

2. GENERAL APPROACH TO PROCESS SIMULATION

During polymer processing operations the material expe-riences simultaneous fluid flow and heat transfer. Flow regimes, depending on the nature of the material, the equipment, and the processing conditions, involve combinations of shear and extensional flows in conjunction with enclosed or

free surface flows. The thermo-mechanical history experienced by the polymer during flow and solidification results in the development of a particular microstructure in the finished article which is closely related to the ultimate properties. Therefore, the optimization of the process and the product must be based on an understanding of the interactions between resin properties, equipment and product design, operating conditions, and ultimate properties of the article.

Mathematical modeling and computer simulation have been employed to extend the scope of the analysis of polymer processing operations, beyond that readily obtainable through experimentation, to gain a better understanding of these interactions.

In general, computer simulations deal with two main aspects, i.e. mathematical model of the process and numerical techniques employed to find and display the solution. A schematic representation of the modeling philosophy is given in figure 1.

2.1 Mathematical Modeling [3,4]

The mathematical analysis of polymer processing operations involves the solution of the equations of conservation of mass, momentum and energy.

The equation of conservation of momentum, also called equation of motion represents the balance between the kinematic (velocity field) and dynamic variables (pressure and stress fields) acting on any given fluid. Due to the vector and tensor characteristics of the velocity and stress fields the equation of motion for an incompressible fluid has three components and involves nine unknowns. Therefore, it is necessary to introduce an expression that relates the velocity and stress fields.This relationship, called " rheological constitutive equation", is used as the defining equation for specific types of material behaviour under flow, i.e. newtonian, purely viscous non-newtonian, viscoelastic, etc.

The equation of conservation of energy represents the balance of heat transfer to and from the system due to convection, conduction, viscous dissipation, phase change, etc.

Furthermore, in the case of compressible fluids, where density variations are important, it is necessary to employ an appropriate "equation of state" to describe pressure-volume-temperature (P-V-T) variations.

In order to solve a particular problem it is also necessary to specify a set of initial and boundary conditions. These are the mathematical representation of the "real" problem to be solved.

In general, polymer processing operations involve the flow of complex fluids in non trivial geometries. An attempt to solve, analytically or numerically, the complete set of conservation equations and boundary conditions becomes a monumental task. Therefore, in many cases assumptions and approximations are employed. These consi-derations have to be established after a careful analysis of the phenomena occurring in the real problem and their validity will determine the success or failure of the proposed model. A general classification of the assumptions most commonly used in simplifying the conservation equations is shown in Table 1 .

2.2 Material Considerations [5]

As has been mentioned before, the choice of an equation of state and/or a rheological constitutive equation is an important factor in the mathematical modeling of the flow in polymer processing operations.

The choice of a particular rheological constitutive equation should be made based on the following criteria. First, it is desirable to select an equation which has the capability of accurately describing the rheological response over a wide range of deformation histories. On the other hand, since this relationship must be utilized in conjunction with the transport equations its mathematical simplicity is of prime concern. Also in this context it is important to bear in mind the characterization problems that are involved in the experimental determination of the material functions associated with the constitutive equation.

Depending on a particular geometric configuration the deformation may be dominated by shear or extension or may involve a combination of both. Shear dominated flows are frequently associated with flows in closed channels or cavities having constant cross sections, whereas extensional flows often accompany deformations in contractions an in certain types of free surface flows. Furthermore, the relative importance of the elasticity of the fluid as compared to its purely viscous nature is a function of the flow kinematics. Consequently it should not be common practice to always insist on using the most complex constitutive model for all purposes; it merely needs to be adequate for the purpose at hand.

The description of the heat transfer characteristics of the material during processing is particularly important in the case of partially crystalline systems since to a large extent they determine the ultimate properties of the finished part.

Finally, it should be desirable to have laws describing the mechanical behaviour (part performance under service conditions) of the part not only as a function of loading conditions (deformation rate, temperature, humidity, etc.) but also as a function of processing variables (temperature, pressure, time).

The integration of all these properties in a material data base will help in establishing a solid R & D strategy that will analyse polymer processing operations from the overall material characteristics - processing conditions - product properties relationship.

2.3 Computational aspects

The resulting system of non-linear partial differential equations representing the phenomena taking place during processing can, in most cases, only be solved using numerical techniques. The two most common numerical schemes are finite difference and finite element methods.

Finite difference techniques are applicable to systems with simple geometries. They provide a discrete solution at specified grid points. These models are specific to the location and geometry of the part to be analyzed. If transient and inertia terms can be neglected and if simple geometrical boundaries are involved an explicit finite difference scheme can be employed. The Marker and Cell techique is an explicit finite difference method that has been successfuly applied to polymer processing operations. For unsteady flows, an implicit finite difference method is used owing to the time interval restrictions as a result of the usually low Reynolds numbers. The Crank-Nicholson is a well known example of implicit finite difference techniques.

Finite element techniques are more versatile in that they are independent of the geometry of the system and are not limited to a specific type of element. Their use has also gained popularity due to the development of solid modeling algorithms capable of representing three dimensional objects having complex surface geometries, using semiautomatic or automatic meshing techniques (topological searching).

3. EXAMPLES OF MODELING IN POLYMER PROCESSING

3.1 Injection Moulding Process [6,7]

Injection moulding is the most important process for the manufacture of three dimensional plastic and rubber articles used in industrial sectors such as automotive, electronics, aerospace, furniture, appliances, household items and packaging.

The materials used in this process range from commodity plastics such as high and low density polyethylene, polystyrene, and polypropylene to the the high performance driven engineering resins such as nylon, ABS,

polycarbonate, PEEK, PES, etc. However, recents trends indicate that injection moulding is being increasingly used in the moulding of advanced materials including ceramics, conductive polymers, liquid crystals, reinforced plastics and metal alloys.

The injection moulding process involves, most commonly, the melting of a material followed by its injection under pressure into a mould where it solidifies. The main components of an injection moulding press are the melt injection unit and the mould clamping unit.

The injection step involves the delivery of the polymer melt from the tip of the screw through the nozzle, sprue, runners and gate into the cavity. After entering the cavity the moulding cycle consists of three main stages. During the filling stage, the polymer melt flows into the mould under pressure. The filling stage is concerned with the transient non-isothermal flow of a viscoelastic fluid. When the cavity is filled, a high packing pressure is applied to force additional polymer into the mould. The purpose of this step, is to introduce sufficient polymer into the cavity in order to compensate for shrinkage during the solidification (cooling) stage. The increase of the density in the cavity is responsible for the rapid increase of the pressure during the packing stage. Cooling is continued until the solidified plastic is rigid enough to be removed from the mould without damage.

In the cooling stage, a continuous decrease in cavity pressure is observed. This stage plays a major role in determining the final properties of the moulded article and consequently it is very important from an economic point of view. However, the thermo-mechanical history experienced by the material during filling and packing has a great influence on the ultimate behaviour of the moulded article.

3.1.1 Simulation Models [8,9]

Most injection moulding simulation models are useful for the prediction of filling time, short shots, pressure distribution, progression of the melt front as a function of time,velocity and temperature distributions, and overall cycle time. When integrated within the frame of CIMP they have also proven to be of great value in the optimization of the design of moulds and delivery channels as well as in product optimization. Figure 2 shows the predicted filling pattern during the injection phase of a complex part.

During recent years, new models have been proposed in order to extend the analysis to obtain information related to the micro-structure (morphology, orientation, frozen stresses, shrinkage,etc.) of the final part and its relationship to product performance. Figure 3 presents results of the stress distribution in a moulded part.

Table 2 presents a summary of some of the simulation models derived to describe certain aspects of the injection moulding process. This table also illustrates where the CIMP oriented models are placed with respect to the overall classification.

Finally, it is evident from the new technological demands imposed on the polymer processing industry, the need for the development of more comprehensive mathematical models and simulation packages. These systems should yield not only information regarding mouldability and thermomechanical history but also regarding product quality and the optimization of resin selection, product and tool design, and operating conditions so that a product of adequate properties may be manufactured with an acceptable cost to performance ratio. This goal can be readily obtained, within the frame of " computer integrated systems " by combining material database, solid modeling, and product/process simulation technologies.

3.2 Blow Moulding Process [12]

Blow moulding is a commercially important polymer processing operation used in the manufacture of hollow plastic articles. Food and beverage containers still represent the most important market for blow moulded plastic products and the applications domain is expanding due to success of multilayer extrusion processes capable of achieving optimum cost/performance ratios and combination of properties. New horizons are also rapidly opening particularly in the automotive, leisure/sporting goods and furniture markets. This growth runs parallel with the development of new high performance materials suited for the three basic variations of the process : extrusion blow moulding, injection blow moulding and stretch blow moulding.

In the extrusion blow moulding process, the raw material is fed to a plasticating extruder in granular or pellet form. The molten material is extruded through an annular die either continuously or intermittently in order to produce a hollow cylindrical tube called parison. Continuous extrusion is normallly employed for small size, high volume parts, whereas intermittent extrusion is typically used for larger size lower volume applications. The annular die may be designed to incorporate an hydraulic mechanism to vary or program the annular gap size. In this way, the extrusion process can be programmed to impart a specific wall thickness distribution or controlled weight to the parison. Once a parison of the desired length has been formed the mould is closed and the parison is infla-ted by internal air introduced through the die-head assembly. The mould walls are vented, and a vacuum may be applied. The molten polymer is thus forced to conform to the shape of the mould cavity. The article is then cooled, solidified and ejected from the mould.

Injection blow moulding is a process in which a preform is injection moulded around a blowing mandrel. The blowing mandrel and moulded preform are rotated to a blowing station having a split mould with the desired shape. The polymer is then inflated and solidified in much the same manner as in the extrusion blow moulding process. Injection blow moulding offers the advantages of accurate dimensional control (through more precise weight and thickness distribution along the preform), elimination of scrap and the moulding of neck threads.

An important variation of either extrusion or injection blow moulding is the so called stretch blow moulding process. In this process the parison or the preform are mechanically stretched before blowing. The result is a lighter product biaxially oriented (axial and radial directions) having better mechanical, optical and barrier properties.

3.2.1 Simulation Models [13]

In the modeling of this process the first objective is the prediction of the wall thickness distribution of the moulded article and in particular the wall thickness distribution along and around the article. Secondly, it is desired to relate the wall thickness predictions with die and mould design. Finally, the ultimate goal is to predict the final properties of the article using material and processing parameters. Figure 4 shows an exploded view of a blow mould .

For the purpose of developing a simulation model of the blow moulding process we will describe it in terms of three distinct and sequential phases, namely, parison formation, inflation and cooling. Moreover, the inflation stage can be further divided into two distinct substages occurring in succession : free inflation which persists until the polymer melt comes into contact with the mould surface; and confined inflation, which occurs when the melt deformation is restricted in certain directions owed to the presence of the mould walls.

The parison formation stage involves the swelling of the parison, in diameter and thickness, coupled to drawdown under its own weight. Consequently, the final parison diameter and thickness are a net result of two competing influences arising from melt elasticity and gravity. This stage is of utmost importance since it is the starting point for the other stages of the process and therefore will influence the wall thickness distribution of the final article. The rheological complexity of predicting parison behaviour arises from the fact that it is a free-surface problem involving time-dependent, non-isothermal elastic recovery from a complex flow of a viscoelastic fluid subject to the force of gravity. Figure 5 shows the relationship between diameter and thickness swell.

The inflation of a viscoelastic parison or preform involves extensional deformations. Since the process is very rapid these deformations can be quite large and the inertia of the fluid can exert a significant influence on the growth dynamics. In the case of products of circular shape the free inflation step assumes an important role in controlling part quality. On the other hand, confined inflation is the key factor when moulding articles of non-circular shape. Figure 6 presents the dynamics of parison inflation.

From the above discussion, the complexity involved in simulating the blow moulding process should be evident. The important phenomena relating to extrudate swell and parison formation have been extensively investigated and are reasonably well understood. However, the application of the published results requires careful consideration owed to the different experimental conditions, theoretical assumptions and specific cases employed by the various research teams (industrial and academic). On the other hand, very limited work has been reported in relation to inflation and cooling behaviour and its relationship with the final properties of the moulded article. Table 3 gives a summary of the most significant developments in the simulation of the blow moulding process.

At the present moment the successful development of an overall simulation model for blow moulding is limited by the following aspects : lack of an appropriate constitutive equation capable of describing the melt behaviour under different deformation regimes; implementation of new numerical techniques(finite elements and finite differences) suitable to deal with highly elastic fluids as well as with large deformations; and reliable experimental techniques that can be used to measure the relevant material properties as well as the key processing parameters.

4. REFERENCES

1. Z. Tadmor, C.C. Gogos, Principles of Polymer Processing, John Wiley, NY (1979).
2. J. Throne, Plastics Process Engineering, Marcel Dekker, NY (1977).
3. J.R.A. Pearson, S.M. Richardson, Computational Analysis of Polymer Processing, Applied Science Publishers, London (1983).
4. M.J. Crochet, A.R. Davies, K. Walters, Numerical Simulation of Non-Newtonian Flow, Elsevier Science Publishers, Amsterdam (1984).
5. R.T. Tanner, Engineering Rheology, Clarendon Press, Oxford (1985).
6. I.I. Rubin, Injection Molding-Theory and Practice,John Wiley (1972).
7. D.V. Rosato (Ed.), The Injection Molding Handbook, Van Nostrand-Reinhold Co., NY (1985).
8. E.C. Bernhardt (Ed.), Computer Aided Engineering for Injection Molding, Hanser Publishers, Munich (1983).
9. L.T. Manzione (Ed.), Applications of Computer Aided Engineering in Injection Molding, Hanser Publishers, Munich (1987).
10. G. Salloum, P. Girard, A. Garcia-Rejon, A. Vinet, IMRI Report No. 87RIS-107-600-C, (1987).
11. M.R. Kamal, F.H. Moy, Chem. Eng. Communications, 12, 253 (1981).
12. D.V. Rosato (Ed.), The Blow Molding Handbook, Hanser Publishers, Munich (1988).
13. A. Dutta,Ph.D.Thesis, State University of New York-Buffalo, (1981).
14. A. Garcia-Rejon, J.M. Dealy, Polym. Eng. Sci., 22, 158 (1982).
15. M.R. Kamal, V.Tan, D. Kalyon, Polym. Eng. Sci., 21, 331 (1981).

LEVEL 0	:	NO ASSUMPTIONS
LEVEL 1	:	ASSUMPTIONS RELATED TO THE MATERIAL PROPERTIES Rheological constitutive equation, equation of state, specific heat and thermal conductivity.
LEVEL 2	:	ASSUMPTIONS RELATED TO FORCES ACTING ON THE SYSTEM Inertial, viscous and gravitational.
LEVEL 3	:	ASSUMPTIONS RELATED TO THERMAL FORCES Conductive, convective and viscous.
LEVEL 4	:	ASSUMPTIONS RELATED TO TIME EFFECTS Steady or unsteady state.
LEVEL 5	:	ASSUMPTIONS RELATED TO THE DIMENSIONALITY OF THE PROBLEM

Table 1. Conservation Equations : Simplifying Assumptions

TABLE 2. CLASSIFICATION OF INJECTION MOULDING MODELS

	FILLING	PACKING	COOLING	PART PERFORMANCE
olution	Material	Material	Material	Material
AN	IN INN		COND COND/CONV	AM shrinkage (combined (with experimental data)
FD	IN INN IVE	CN CVE	COND	AM microstructure (crystallinity, orientation) CRY
CV	IN INN		COND	
FE	IN INN		COND	thermal/stress analysis

SOLUTION	MATERIAL
A : analytical	IN : incompressible newtonian
FD : finite difference	INN : incompressible non-newtonian
FE : finite element	IVE : incompressible viscoelastic
C : control volume	CN : compressible newtonian
	CVE : compressible viscoelastic
	CRY : crystalline
	AM : amorphous
	COND : conduction
	CONV : convection

TABLE 3. CLASSIFICATION OF BLOW MOULDING MODELS

	Parison		Preform *	Inflation		Cooling	Part Performance
	Swell	Sag		Free	Confined		
olution	Material		Material	Material		Material	Material
	IN	IN					
AN	IEL			IEL	IEL	COND	
	IVE	IVE		IVE	IVE	COND	
	IN	IN	IN				
)	IEL		INN	IEL	IEL	COND	
	IVE	IVE	IVE	IVE	IVE	COND	
	IN	IN	IN				
E	IEL		INN	IEL	IEL	COND	stress/ thermal analysis
	IVE	IVE	IVE	IVE	IVE	COND	

* : includes control volume (CV) approach

SOLUTION

AN : analytical
E : finite difference
E : finite element

MATERIAL

IN : incompressible newtonian
INN : incompressible non-newtonian
IEL : incompressible elastic
IVE : incompressible viscoelastic
COND : conduction

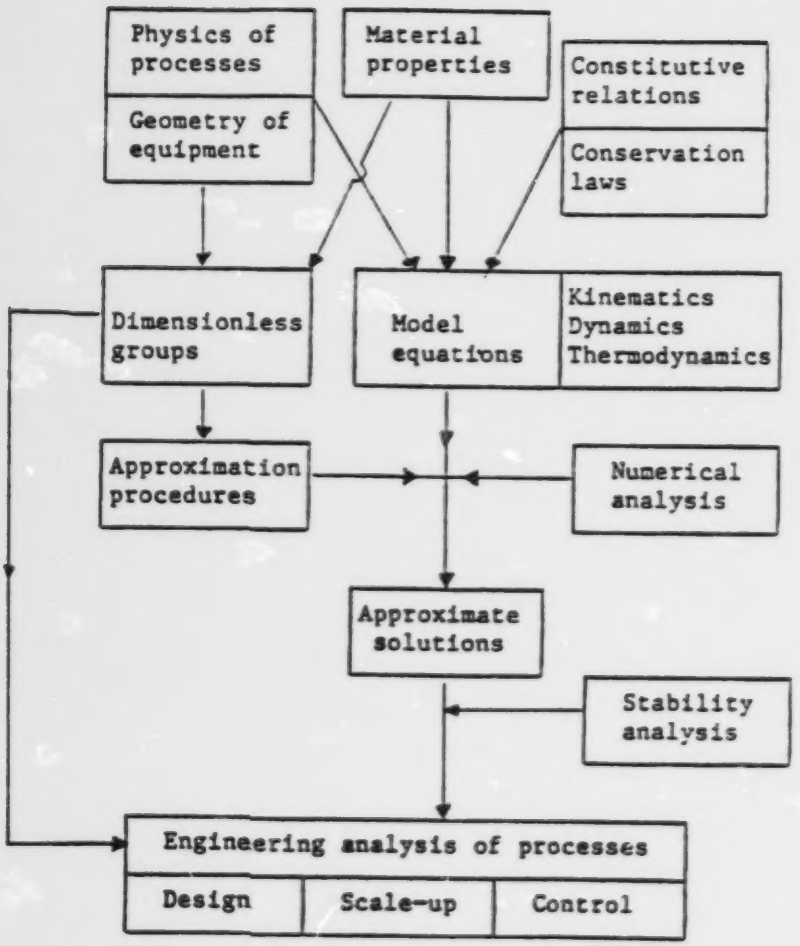
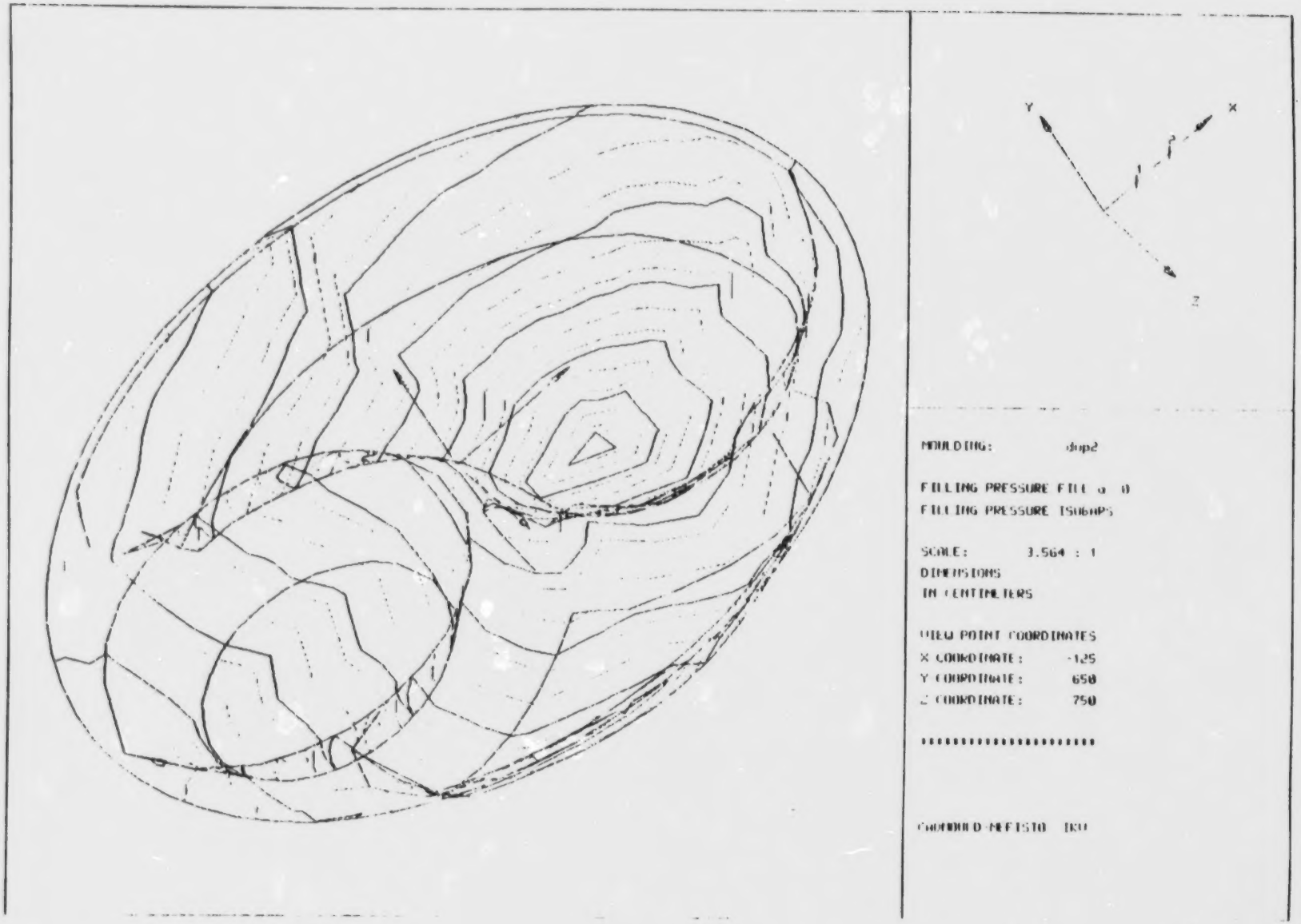


Figure 1: Modeling Philosophy

FIGURE 2. PREDICTION OF FILLING PATTERN AND ISOBARS.



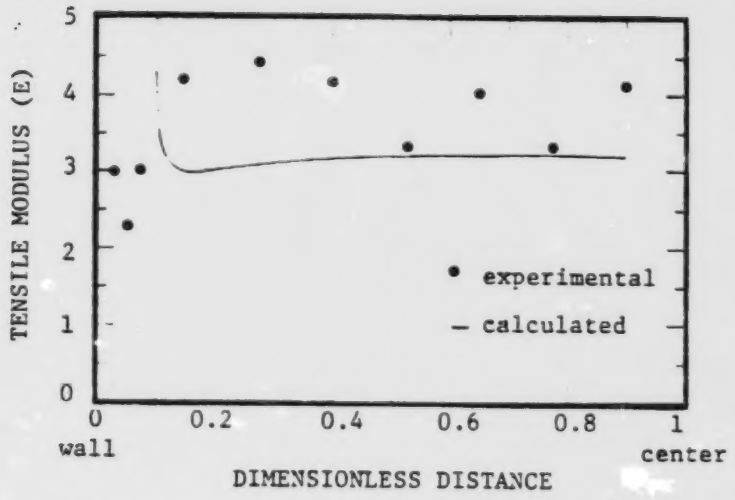


Figure 3. Experimental and calculated tensile modulus at the center of cavity. (11)

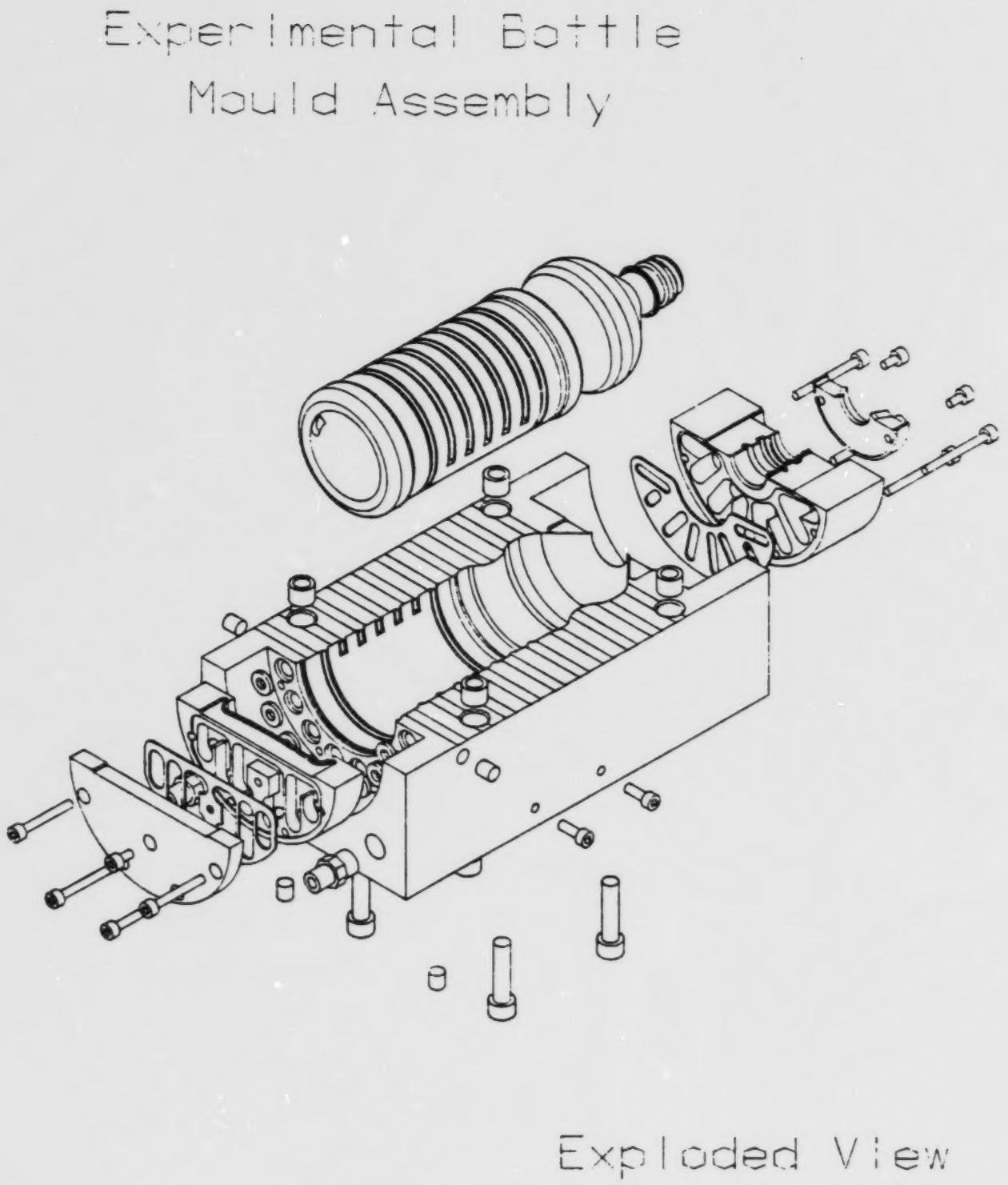


Figure 4. Experimental Bottle Mould Assembly.

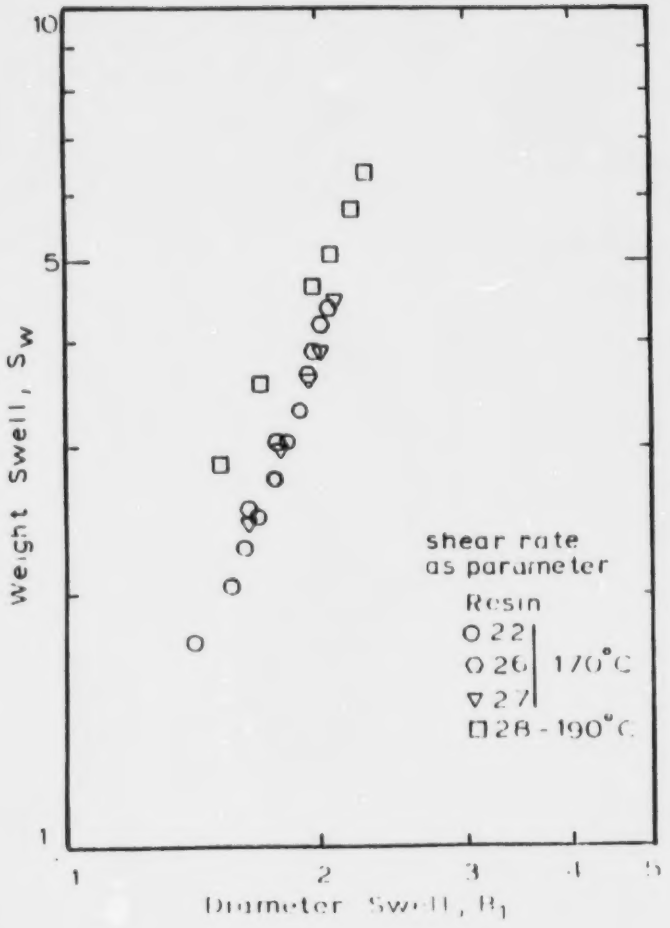


Figure 5a. Comparison between diameter and weight swells (14)

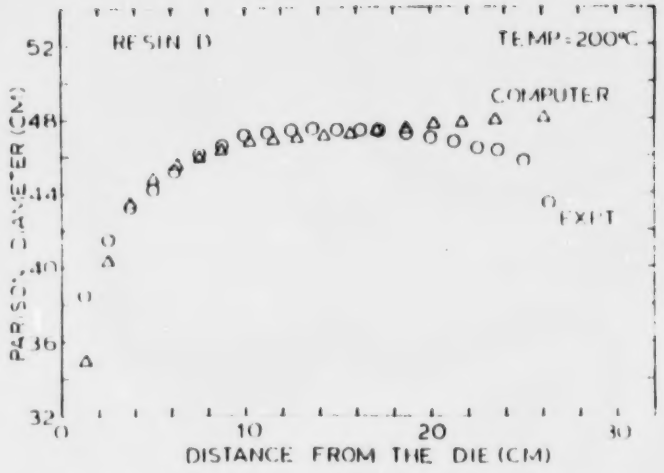


Figure 5b. Comparison of Calculated and Experimental Parison Diameter Distributions for HDPE (15)

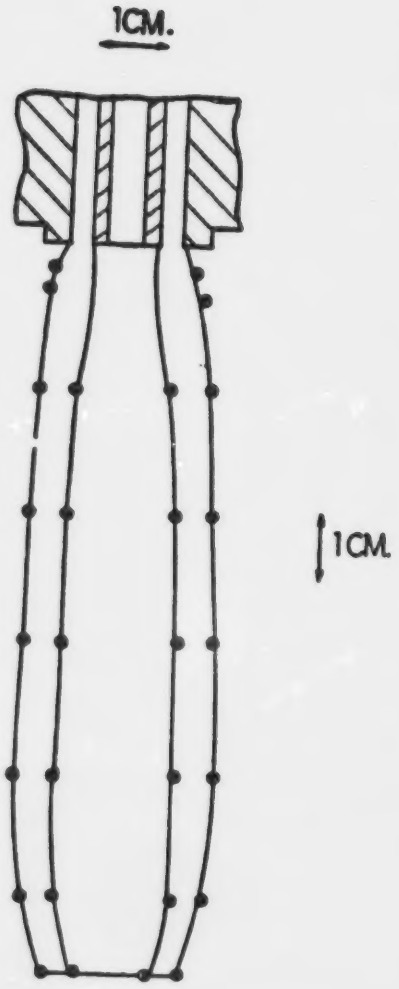


Figure 6a. Typical Parison Profile

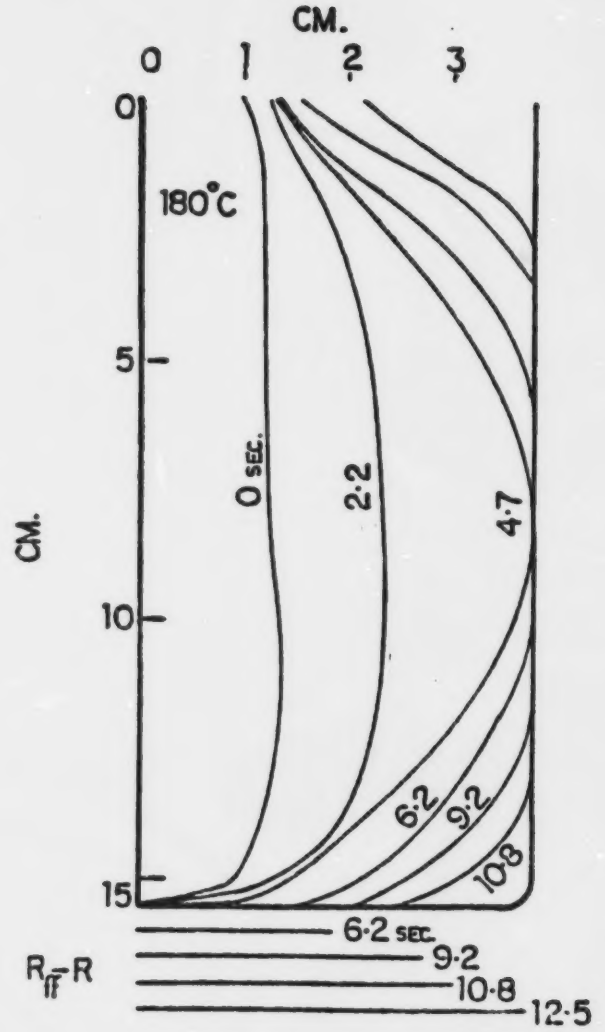


Figure 6b. Parison Inflation within a Square Mould Cavity (13)

EXTRUSION PROCESSES

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1. INTRODUCTION [1,2]

Plastics extrusion is basically defined as converting plastic powder or granules into a continuous uniform melt and forcing this melt through a die which yields a desired shape. The output from the extruder can be an end-product or it can be an intermediate step in polymer processing operations such as film blowing, blow moulding, calendering, film and wire coating and thermoforming.

The most common end-products include pipe; tubing; fibers; sheet (window glazing, foam); and custom profiles (auto trim, window and house sidings, edge trim, etc.).

The polymers used in the extrusion processes include most thermoplastic materials both unreinforced and reinforced.

Presently, the extrusion process is being used extensively due to the growing importance of plastics in such industrial sectors as packaging, building and construction, and automotive; and also as a result of the advances in machine technology (coextrusion, twin screw extruders, etc.), process control strategies, die design, and downstream equipment (hauloffs and gaging systems, etc.). Table 1 presents a classification of extruders used in the plastics industry.

The versatility and modular characteristics of the extrusion process and its derived polymer processing operations made them ideal candidates for the application of a "Computer Integrated Materials Processing - CIMP" application.

2. DESCRIPTION OF THE BASIC EXTRUSION PROCESS [3,4]

Figure 1 shows a schematic representation of a typical single-screw extruder.

Solid polymer in the form of granules or powder is usually gravity-fed through the hopper. After entering the helical screw channel the material is conveyed along the screw and heated inside the barrel, with the goal being to reach the die system in a completely molten state, having a uniform temperature, and being pumped at a constant output rate. The barrel is heated and cooled by heater/cooler jackets surrounding its outer wall to aid in the melting of the material in the screw. These heater/coolers are arranged on the barrel in several zones which are separately controlled to the desired temperature. The screw is driven by a motor which speed is reduced and its torque increased through a gear reducer. The gear case also houses a thrust bearing to counter the forces due to die pressure and conveying forces of the material on the screw. In most cases, a breaker plate supporting a screen pack is placed between the end of the screw and the die. This device prevents contaminants from reaching the die and also helps in homogeneizing the melt.

The screw is the heart of the extrusion process and its design determines to a large extent the quality of plastication, mixing, and pumping performance. In general, screws are divided in three basic sections, namely, feed, compression and metering. In the feed section the channel is rela-

tively deep and its main function is to convey and compact the solids. The compression section owes its name to its progressively decreasing channel depth. Melting occurs at this stage as a result of the supply of heat from the barrel and mechanical work from the rotation of the screw. The shallow metering section, which is of constant depth, is intended to control the output of the machine, generate the necessary delivery pressure and mix the melt. Figure 2 shows some of the most common screw designs.

An extrusion die consists of a set of flow channels designed to convert the melt output from the extruder into a continuous and uniform extrudate of the desired cross-sectional shape. Most dies start with a wide distribution channel which feeds the melt to the final narrow forming channels which help to meter the flow.

The overall performance of an extrusion line will be determined by both the operating characteristics of the extruder and the die. Therefore any attempt to optimize the process has to deal simultaneously with these two important aspects.

3. MATHEMATICAL MODELING [5,6,7]

The mathematical modeling of the extrusion process includes the analysis of the phenomena of solids conveying, melting of the resin, pumping and pressurization (melt flow in the extruder), and finally the flow in the die.

3.1 Solids Conveying

In comparison with the large amount of research on melt flow in screw extruders, relatively little attention has been given to the conveying of solid granules from the hopper to the position at which a significant amount of melting has occurred. There are several reasons for this. Solids conveying is usually a relatively minor part of the overall extrusion process, and occurs only over the first few turns of the screw. It rarely controls directly the output from the machine which is normally determined by the later melting and melt-pumping processes.

Most analyses of solids conveying ignore the particulate nature of the polymer and assume that the material in the channel follows a plug flow, therefore ignoring the effects of stresses and deformations within the bulk of the solid.

The relative motions of the screw, solid plug and channel are such, however that frictional forces generate not only a pressure gradient in the downstream direction but also one in the transverse direction. Since in a typical extruder the length of screw channel over which friction conditions exist is of the order of at most 10 times the channel width, the pressure difference across this width is likely to be significant compared to the pressure built up in the downstream direction. The two-dimensional case has to be solved using numerical techniques while the one-dimensional approximation (the solution most commonly used) can be obtained analytically. However, one of the main difficulties in applying any analysis of solids conveying lies in the uncertainty regarding the values for the

coefficients at friction.

3.2 Melting of the Resin

The primary purpose of a theoretical model for the melting in an extruder is the prediction of the amount of unmelted polymer at any point in the extruder channel, the screw length required to melt all the polymer and the dependence of these two variables on the nature of the polymer, the screw geometry, and the operating conditions.

In the melting zone the solid bed slides down the channel like a nut on a screw. Upon reaching the heated section of the barrel (or earlier if the frictional heat at the barrel is not efficiently removed) a thin molten film is formed between the barrel surface and the solid bed. Two sources of energy cause the melting: heat conduction from the barrel to the melt film - solid bed interface; and heat generated by viscous dissipation caused by the shearing between barrel and solid bed. The film thickness increases in the down channel direction until it exceeds the flight clearance. At this point the "leading flight" scrapes off the melt from the film creating a "melt pool" at the leading flight and segregating the slowly deforming solid bed at the trailing flight (Figure 3). Due to the drag induced by the cross channel component of the screw velocity the melt from the film is continuously removed into a mildly circulating melt pool and a relatively thin film is maintained. The helical solid bed slides slowly down the channel and as it melts the width of the bed decreases and that of the melt pool increases. Figure 4 shows the cross sections of the extruder channel for different melting models. The differences between these models lie in the different functional forms assumed by the solid bed downstream velocity; in the analysis of both upper and lower melt films; and in the assumptions made for the flow and heat transfer in the films, bed and melt pool regions. Furthermore, depending on the previous assumptions an analytical or numerical (finite difference-based) solution can be obtained.

The main input data required for a melting analysis are the extruder geometry, material properties and operating conditions such as mass flow rate, screw speed and temperatures at the barrel and screw surfaces. The information obtained from the melting models includes the variations in the downstream direction of the solid bed width and velocity; upper and lower film thicknesses; pressure and pressure gradients; and required screw drive power and heating/cooling capacity.

3.3 Melt Flow in the Extruder

The objective of modeling this zone is to predict the velocity, temperature and pressure profiles in the screw channel given the screw geometry, rheological and thermal properties of the melt, operating conditions and the rate of melting in the melting zone.

In the past, several models have been developed to predict the flow characteristics in the metering zone. The basic assumptions used can be summerized as follows. Since the screw channel is relatively shallow it is reasonable to assume that it can be unrolled and treated as rectilinear. Moreover this supports the use of the lubrication approximation.

It has also been assumed that inertia and gravitational forces can be neglected allowing to treat the system as a rotating barrel around a stationary screw. The flow may be considered as a combination of pressure and drag flows. For example, a complete 2D approach seeks numerical solutions to a set of four simultaneous coupled second-order non-linear partial differential equations (conservation of mass, momentum and energy); two equations governing transverse flow; and two other equations describing downstream flow and heat transfer. However, according to the type of material and the thermal regime to be considered, four general categories of models can be described: isothermal newtonian flow (analytical solution); isothermal non-newtonian flow (numerical solution); fully developed non-isothermal non-newtonian flow (mostly finite differences); and developing non-isothermal non-newtonian flow (finite differences).

Fully developed solutions provide a considerable amount of insight into the details of the velocity and temperature profiles in the extruder channel. However they present the drawback that thermally fully developed conditions are frequently not reached even at the delivery end of the screw. Developing flow solutions require the knowledge of a temperature profile at the beginning of the melt flow and consequently the calculations are more elaborate.

These two categories of models provide information related to average temperatures (detailed temperature profiles in the case of developing flow); pressure and velocity profiles; required screw drive power and heating/cooling requirements; and mean distributive mixing.

Figure 5 shows typical results for the overall simulation of an extruder.

3.4 Flow in Extrusion Dies [8,9,10]

A die flow analysis is usually carried out with one of two possible objectives in view. The first of these is simply to calculate the pressure drop across the die and the extrudate shape to be expected from a given die geometry run under specific operating conditions. The alternative objective is to establish a flow channel geometry that gives the required extrudate shape, a problem for which a number of different solutions are possible. In practical die design, a further consideration is that the die body must be robust enough for deformations produced by the internal pressures to cause insignificant changes in the flow channel dimensions. Figure 6 describes the methodology involved in the design of a profile die as seen in the context of "Computer Integrated Materials Processing - CIMP".

The pressure drop across the die calculations have been successful for a large number of simple and complex geometries. The predictions include both, isothermal and non-isothermal,analytical and numerical (finite differences and finite elements) solutions dealing with newtonian, non-newtonian and viscoelastic fluids. Figure 7 shows the isobars on a cross section of a profile die.

The prediction at the extrudate shape is closely related to the prediction of the swell of the material as it comes out of the die. The rheological complexity of predicting extrudate swell arises from the fact that it is a

free surface problem involving time-dependent, non-isothermal elastic recovery from a complex flow of a viscoelastic fluid. Mostly due to a lack of an appropriate constitutive equation describing the material behaviour under different deformations; and of more powerful numerical techniques capable of analyzing high elasticity flows the die swell problem remains one of the challenges in polymer flow simulation.

The extensive work that has been done in predicting the swell from cylindrical, slit and annular dies has resulted in a fairly good understanding of the problem. However, this is not the case for the more geometrically complex 3D extrusion dies.

For these reasons, alternative approaches have been developed to predict the flow of the material within and as it comes out of the die. One of these techniques applied over a finite number of control volumes, is the so called lumped parameter method (LPM). Its application to the design of a profile die is presented in Figures 8 and 9.

Finally, it should be mentioned that it is outside the scope of this review, to comment on some of the other important extrusion-based polymer processing operations. The simulation models for processes such as blow moulding [11] film blowing [12], wire coating [13], and calendering [14] are much more complex since they involve not only the flow in the die but the phenomena occurring outside of it.

4. REFERENCES

1. M.J. Stevens, Extruder Principles and Operation, Elsevier Science Publishers, NY (1985).
2. M.H. Naitove, Manufacturing Outlook, Plastics Technology, 34 (1), 40 (1988).
3. Z. Tadmor, I. Klein, Engineering Principles of Plasticating Extrusion, Van Nostrand, NY (1970).
4. C. Rauwendaal, Polymer Extrusion, Hanser Publishers, NY (1985).
5. J.R.A. Pearson, S.M. Richardson, Computational Analysis of Polymer Processing, Applied Science Publishers, London (1983).
6. Z. Tadmor, C.C. Gagos, Principles of Polymer Processing, John Wiley, NY (1979).
7. R.T. Fenner, Extruder Screw Design, Iliffe, London (1970).
8. J. Vlachopoulos, P.S. Scott, Advances in Polymer Technology, 5 (2), 81 (1985).
9. J. Vlcek, J. Vlachopoulos, J. Perdikoulias, International Polymer Processing II (3/4), 174 (1988).
10. A. Karagiannis, A.N. Hrymak, J. Vlachopoulos, AICHE J. (in press) (1988).
11. A. Dutta, M.E. Ryan, J. Non-Newt. Fluid Mech., 10, 257 (1982).
12. J.R.A. Pearson, C. Petrie, J. Fluid Mech. 42, 609 (1970).
13. M. Viriyayuthakorn, R.V. DeBoo, SPE Tech. Papers, 29, 178 (1983).
14. C. Kiparissides, J. Vlachopoulos, Pol. Eng. Sci., 16, 712 (1976).

TABLE 1. CLASSIFICATION OF POLYMER EXTRUDERS

Screw Extruders (Continuous)	Single Screw Extruders	- Melt Fed or Plasticating - Single Stage or Multi Stage - Plastic vs. Rubber Extruder
	Multi-Screw Extruders	- Twin Screw Extruder - Gear Pump - Planetary Gear Extruder - Multi (>2) Screw Extruder
Disk or Drum Extruders (Continuous)	Viscous Drag Type Extruders	- Spiral Disk Extruder - Drum Extruder - Diskpack Extruder - Stepped Disk Extruder
	Elastic Melt Extruders	- Screwless Extruder (Maxwell) - Screw/Disk Extruder (USSR)
Reciprocating Extruders (Discontinuous)	Ram Extruders	- Melt Fed Extruder - Plasticating Extruder (Capillary Rheometer)
	Reciprocating Screw Extruders	- Plasticating Unit in Molding Machines - Compounding Extruders (Ko-Kneader, Pulsating Action)

CLASSIFICATION OF TWIN SCREW EXTRUDERS

Intermeshing Extruders	Corotating Extruders	- Low Speed Extruders (profile extrusion) - High Speed Extruders (compounding, devolatilization)
	Counterrotating Extruders	- Conical Extruders (profile extrusion) - Cylindrical Extruders (profile extrusion)
Nonintermeshing Extruders	Counterrotating Extruders	- Equal Screw Length - Unequal Screw Length
	Corotating Extruders	- Not used in practice
	Coaxial Extruders	- Inner Melt Transport Forward - Inner Melt Transport Rearward - Inner Solids Transport Rearward - Inner Plasticating, Rearward Transport

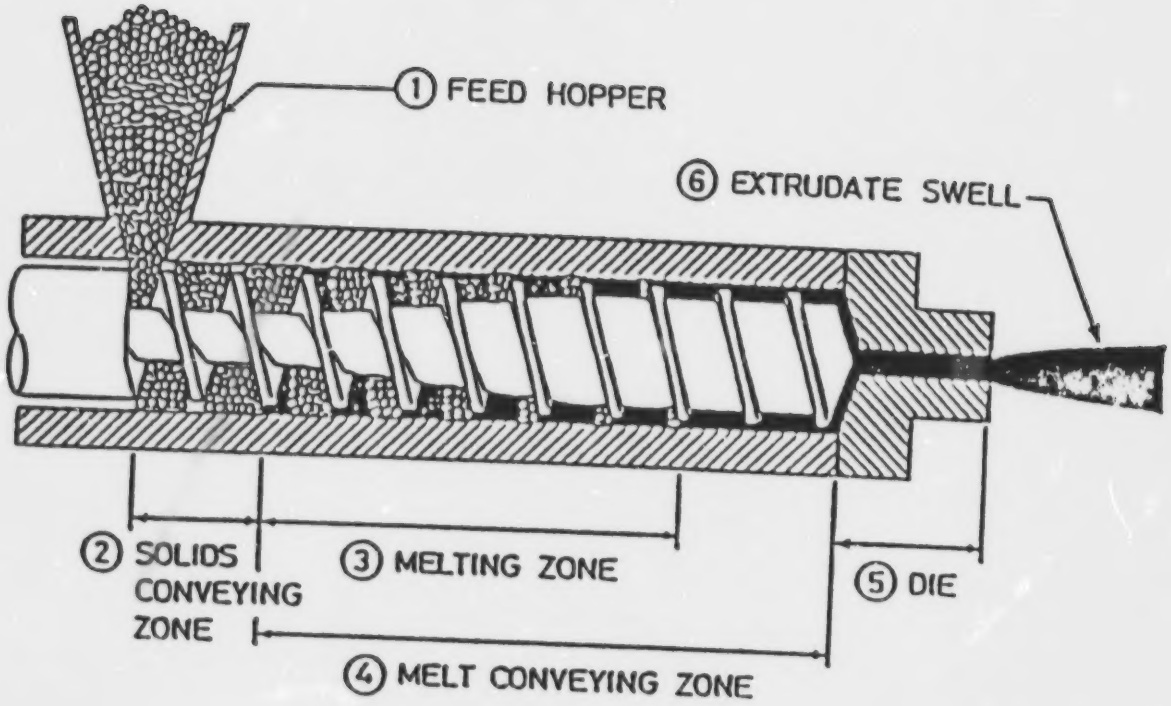


FIGURE 1. SCHEMATIC DIAGRAM OF AN EXTRUDER

FIGURE 2. SINGLE FLIGHTED EXTRUDER SCREWS

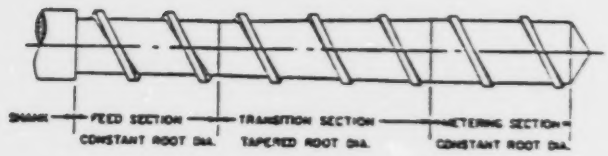


Figure 2a The Standard Extruder Screw

Figure 2b Standard Screw with Additional Flight in Feed Section

Figure 2c Variable Pitch Extruder Screw, Increasing Pitch

Figure 2d Variable Pitch Extruder Screw, Reducing Pitch

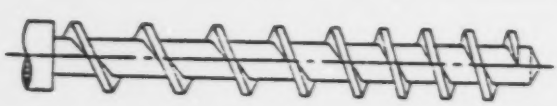


Figure 2e Zero-Meter Screw

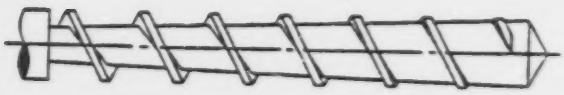


Figure 2f Zero-Feed, Zero-Meter Screw

Figure 2g Rapid Compression Screw

Figure 2h Decompression Screw

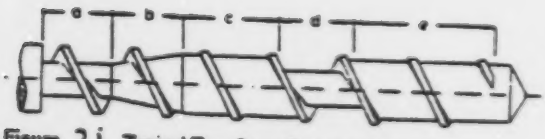


Figure 2i Typical Two-Stage Extruder Screw

a. Feed section
b. Compression section
c. Metering section
d. Extraction section
e. Pump section

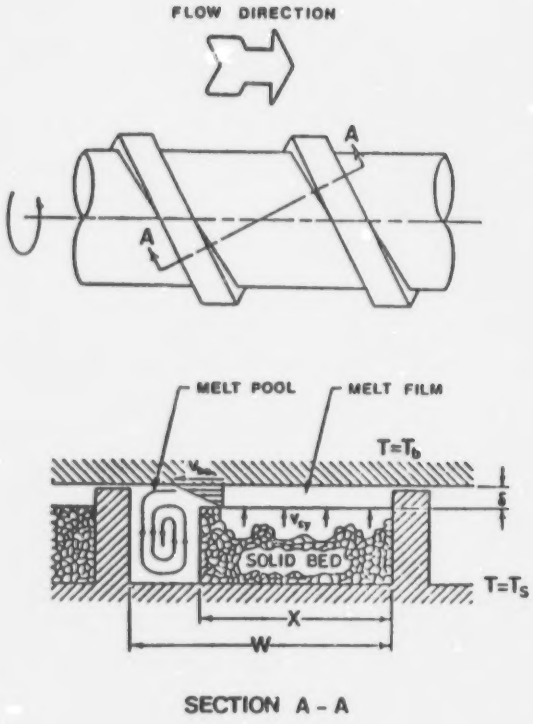


FIGURE 3. Idealized cross-section of the screw channel in the melting zone.

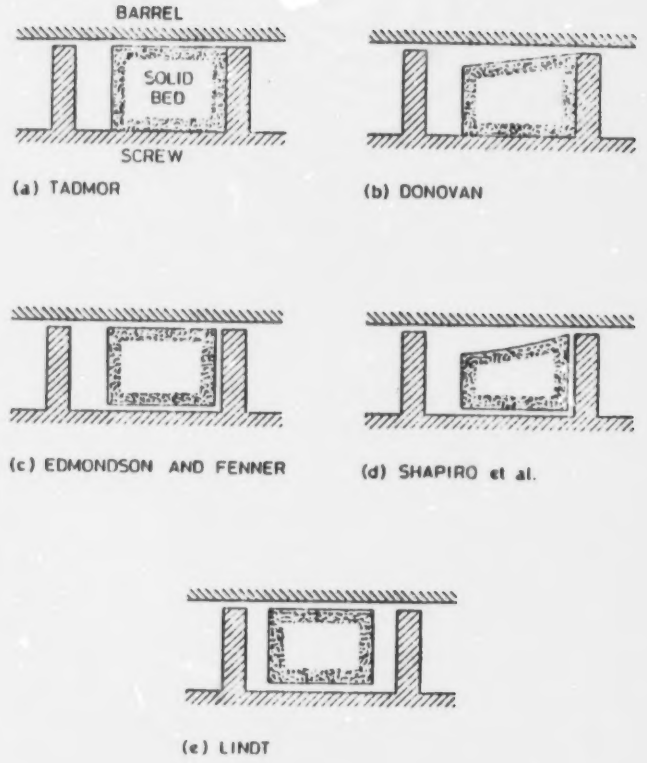
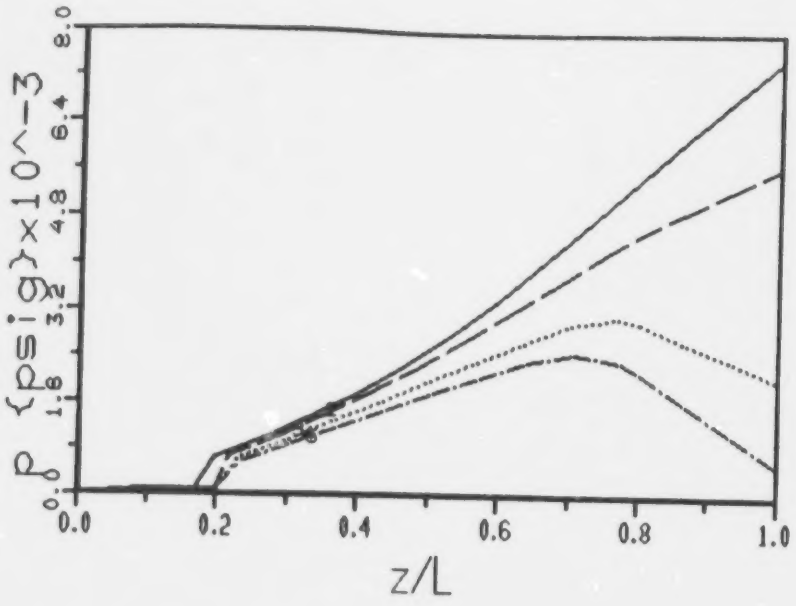
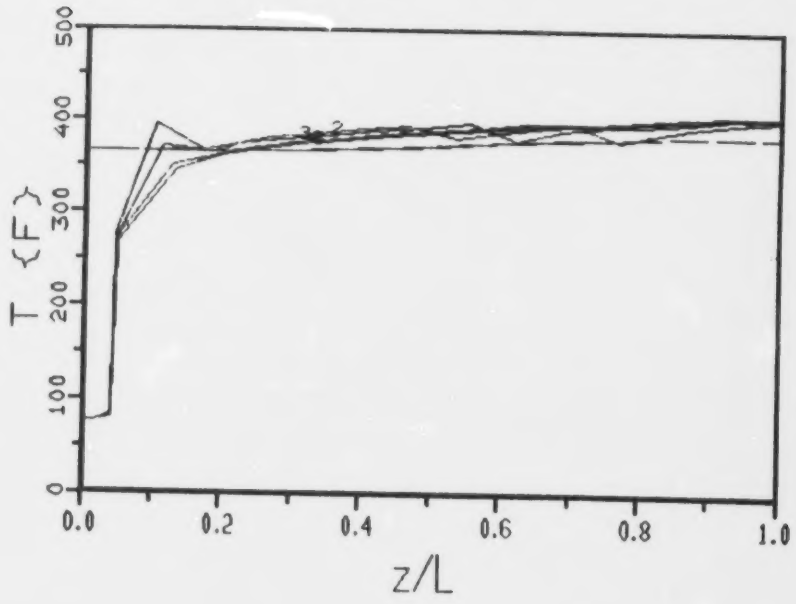


FIGURE 4. Schematic cross-sections of the extruder screw channel for the various melting models.





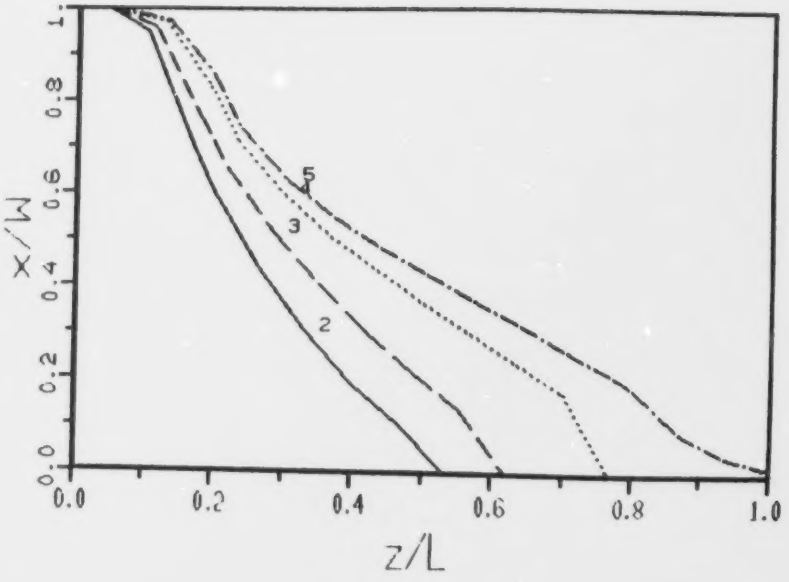


FIGURE 5. TYPICAL EXTRUSION SIMULATION RESULTS.

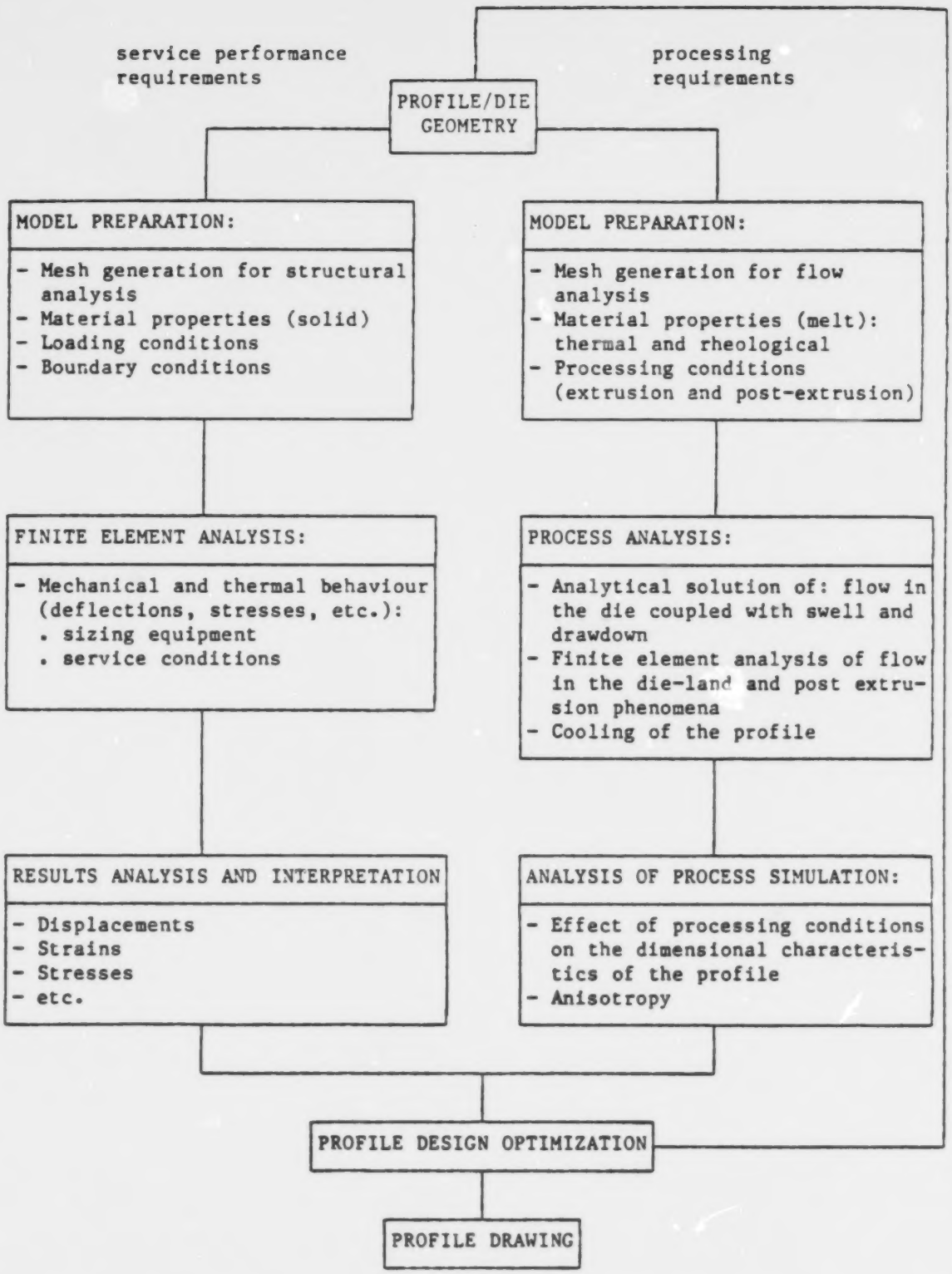
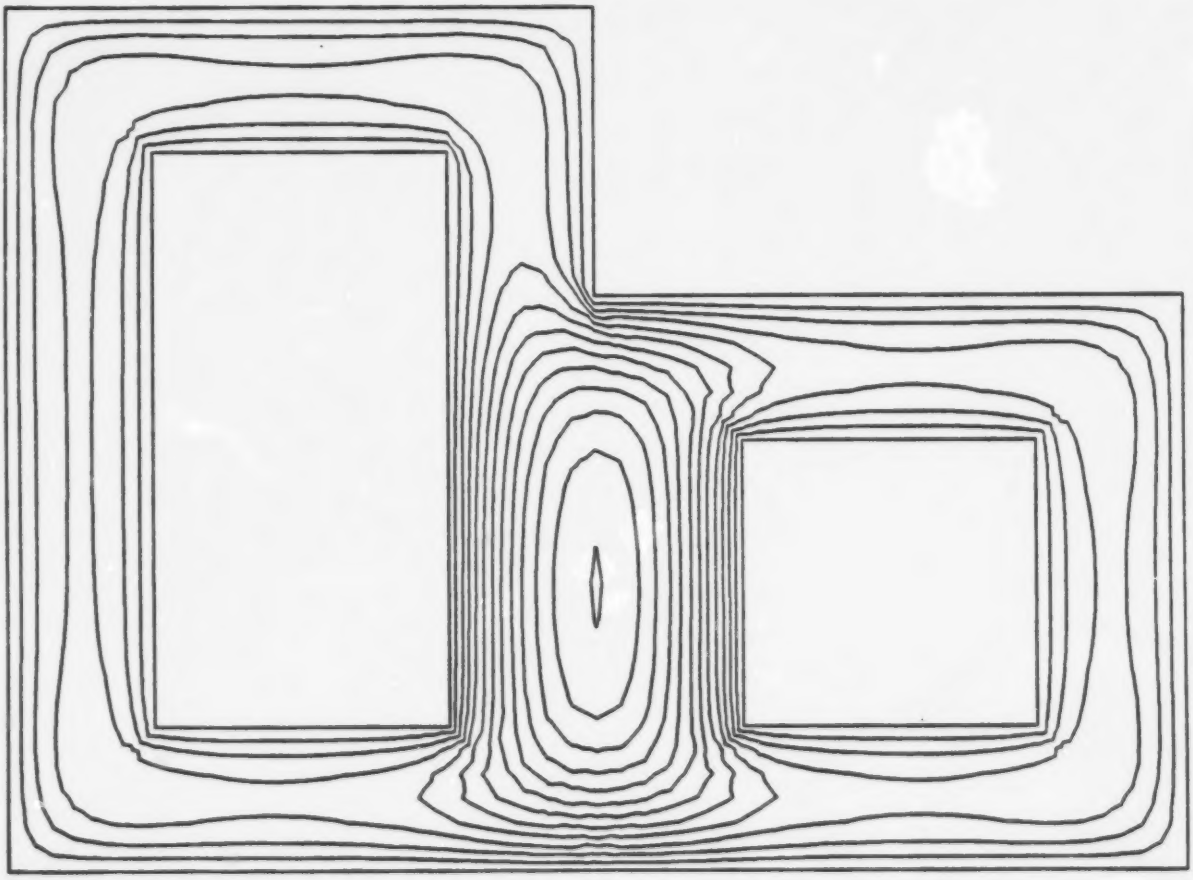
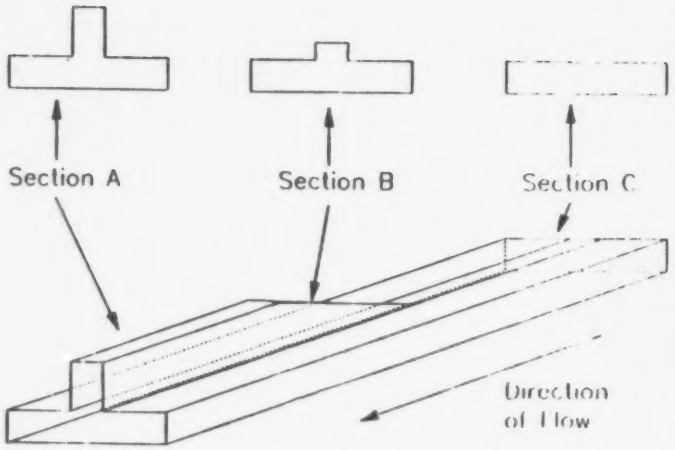

service performance requirements
processing requirements
PROFILE/DIE GEOMETRY
MODEL PREPARATION:
- Mesh generation for structural analysis
- Material properties (solid)
- Loading conditions
- Boundary conditions
MODEL PREPARATION:
- Mesh generation for flow analysis
- Material properties (melt): thermal and rheological
- Processing conditions (extrusion and post-extrusion)
FINITE ELEMENT ANALYSIS:
- Mechanical and thermal behaviour (deflections, stresses, etc.):
. sizing equipment
. service conditions
PROCESS ANALYSIS:
- Analytical solution of: flow in the die coupled with swell and drawdown
- Finite element analysis of flow in the die-land and post extrusion phenomena
- Cooling of the profile
RESULTS ANALYSIS AND INTERPRETATION
- Displacements
- Strains
- Stresses
- etc.
ANALYSIS OF PROCESS SIMULATION:
- Effect of processing conditions on the dimensional characteristics of the profile
- Anisotropy
PROFILE DESIGN OPTIMIZATION
PROFILE DRAWING

Figure 6 : Methodology for profile extrusion die design

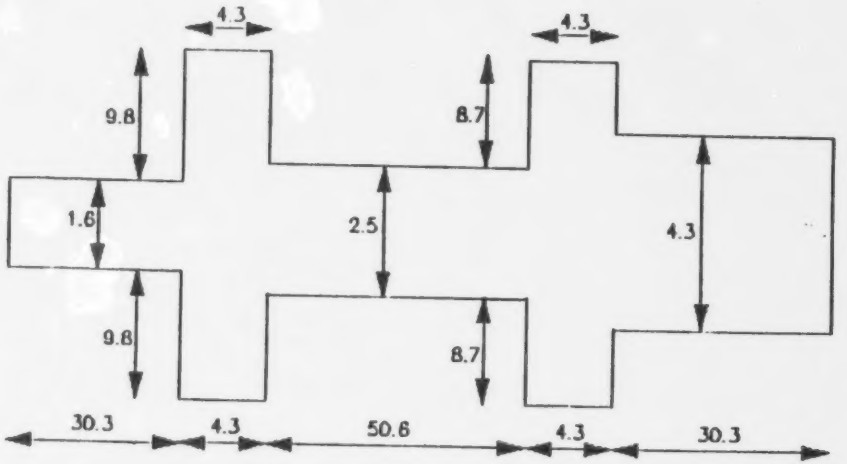
FIGURE 7. Isobars for the flow of a non-newtonian fluid in a profile die (finite element method)



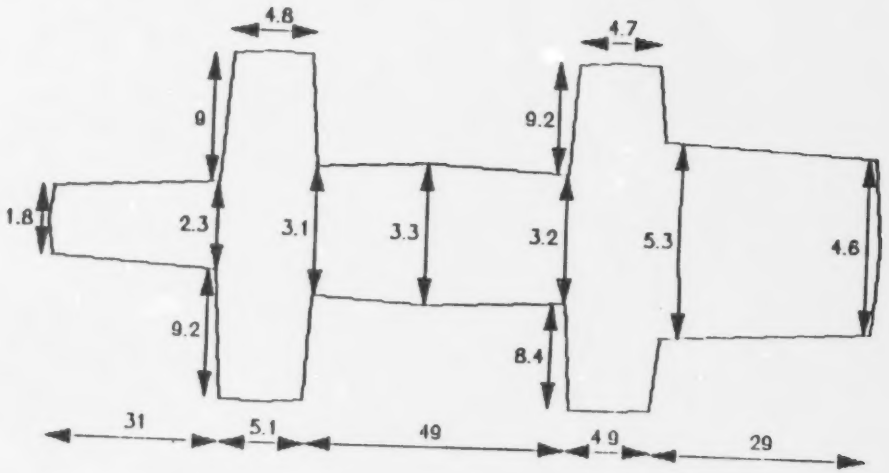


Development of a 'T' element in a profile die.

FIGURES 8 & 9. PROFILE DIE DESIGN.



Dimensions of profile designed by LPM



Dimensions of profile produced from the die given above.

CIMP and Process Simulation - Die Casting Operations

by

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ABSTRACT

This article describes the features of the Computer Integrated Die Casting (CIDC) System, presently being developed at the Industrial Materials Research Institute (IMRI) in cooperation with several Canadian die casting companies. At this stage, the integration of the principal functions has been achieved. Some functions that have been developed separately are being prepared for integration while work continues on others, to broaden the scope of integration.

Application of the CIDC system will be demonstrated on examples of part definition, process simulation and presentation of the results for an automotive part.

INTRODUCTION

The CIDC system does not only assist die designers and die casters in the rapid evaluation of products and processing, but also assures a greater consistency and lowers the chances of errors by absorbing all the generally accepted practical rules as well as the knowledge and judgement of the experts. Furthermore, it lends itself for continuing development and customizing according to specific practices and requirements of the particular installation. It permits use of the retained results for a future reference. Transfer of information and knowledge within an enterprise is made easier and faster. Finally, one should not forget that an important benefit of such system is also the fact that it facilitates gaining much better insight into the die casting process itself.

GENERAL DESCRIPTION OF THE COMPUTER INTEGRATED DIE CASTING SYSTEM

The complete CIDC system is presented in figure 1. The functions presently integrated into the system include product design, material selection, generation of a flat pattern representation, segmentation into flow elements, material databases, non-isothermic process simulation, cooling phase analysis, graphic interpretation of the simulation results, mechanical analysis and generation of files for finite element analysis. Process control and die and product design are under development.

The complete CIDC system employs solid modeling in representing complex geometries of products and tooling for efficient generation of data for the analyses, as well as for effective visualization tool and means of communication. Extensive libraries of geometry primitives, parametrically defined, are used to permit rapid construction of any standardized portions of the model.

The processing module assists the user by supplying the typical processing variables in an informative manner, letting him select the actual variables according to his experience. The heart of the system is the Engineering Analyses module with the capability of analysis of flow, cooling and mechanical performance in service. The required engineering simulations depend on sufficient understanding of all the physical processes involved. The complex nature of the metal flow into the die cavity presents the main problem when mathematically modeling the filling stage. To overcome this difficulty, the CIDC system is presently limited to parts which can be approximately developed into a flat pattern.

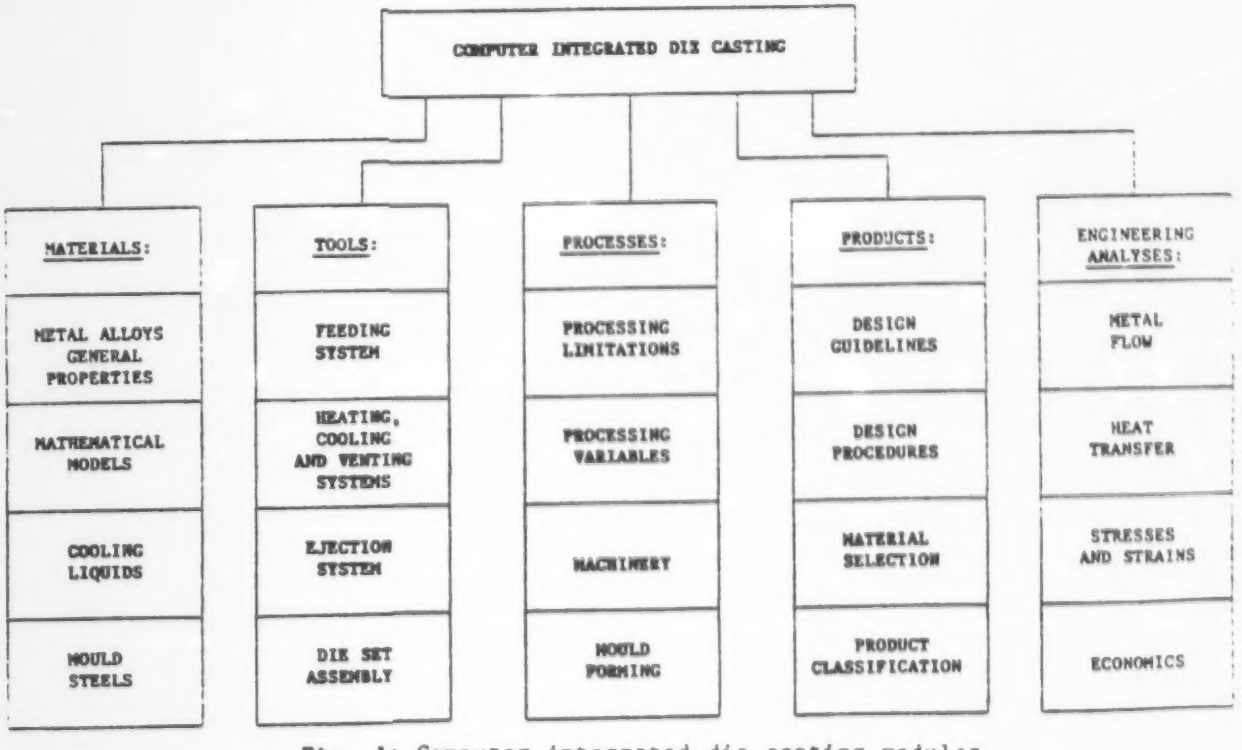

Fig. 1: Computer integrated die casting modules

PRODUCT DEFINITION AND MATERIAL SELECTION

Using the material selection facility, the user can define the range of material properties to represent the service conditions and the system returns a list of available materials for the conditions specified. The load, the temperatures and other environmental constraints will effect the selection of materials. The comprehensive database contains not only the standard material characteristics, but also the data describing their variation within the limits of realistic production parameters. Presently such data is stored for fifteen die casting alloys of zinc, aluminum and magnesium.

To define the product, the graphic facilities are used together with material dependent design guidelines to create a three dimensional model of the product. An example of an automotive part - an axle tube - is shown on figure 2. A preliminary structural analysis of the product may be used to support the choice of the principal dimensions or to signal a need for design modifications. This minimizes the need for product modifications during subsequent detailed analyses or even during the prototype runs.

DESIGN OPTIMIZATION BY PROCESS SIMULATION

To simulate the process of casting, a flat layout pattern of the part is created semi-automatically from the boundary representation of the solid model of the part. The flat pattern has to be then subdivided (figure 3) into the flow elements grouped into the anticipated flow directions, relying on users expertise. Next, the initial segmentation is transferred to the flow simulation

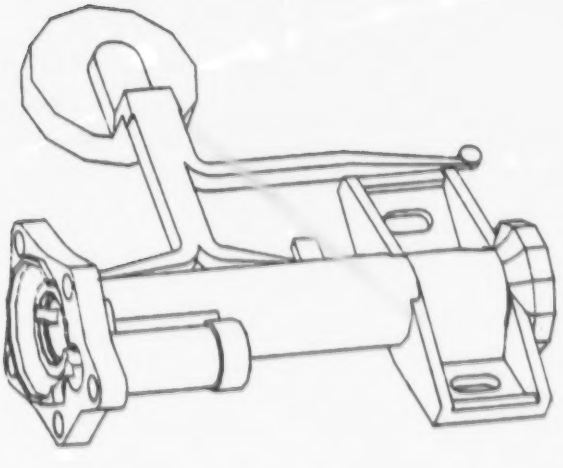

Fig. 2: Three-dimensional model of axle tube casting

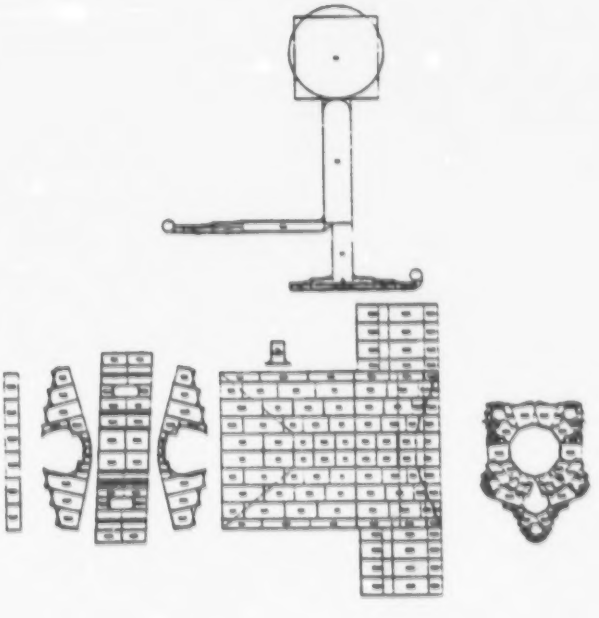

Fig. 3: Segmentation for filling analysis

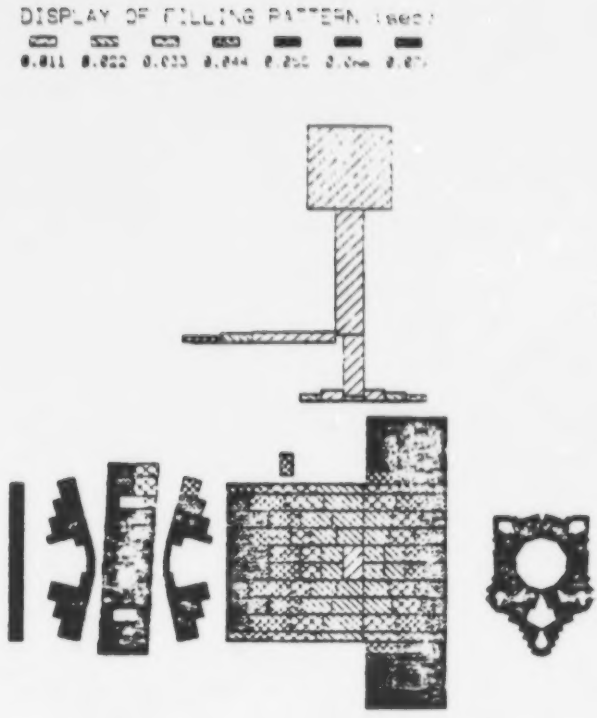

Fig. 4: Filling Pattern

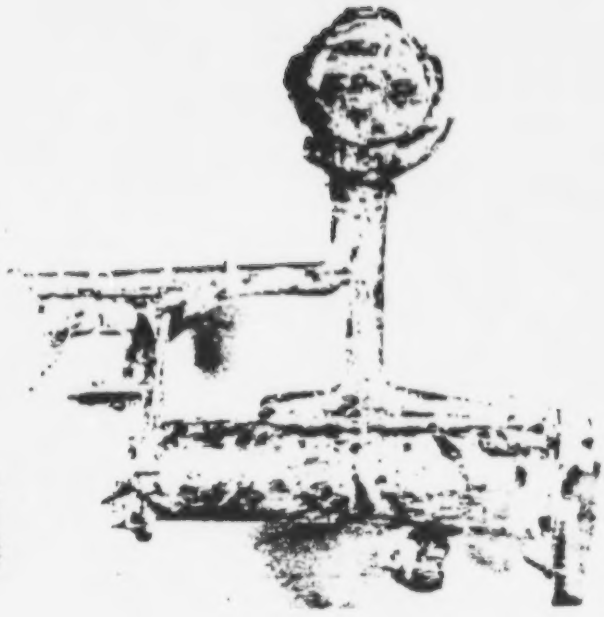

Fig. 5: Short Shot

module, where the elements are further automatically subdivided according to the flow resistances in the flow directions. The flow fronts are defined. Analytical formulae are used in the simulation, to predict the pressures, pressure gradients and temperatures for the non-isothermal flow.

The results of the simulation are first displayed in a tabular form, for the elements of the original geometrical segmentation. At this stage the user can judge the adequacy of the preselected flow distribution and make modifications if necessary. Using the graphic facilities, he can also visualize the analytical results in a form of flat pattern displays (figure 4) or in the form of graphs (figure 6). Possible formation of defects such as formation of weldlines or porosity can be detected here. An example of a simulation of a filling pattern in figure 4 shows a good agreement with the actual partially filled cavity (figure 5).

After obtaining satisfactory simulation of the filling process, the user proceeds with the design of the feeding system with the assistance of a parametric database covering all the standard components. A rapid design is made possible by built-in common design rules as well as manufacturing and process related guidelines. Interactive graphic menus using parametric design approach are used to assist in selection and design of sprues, runners and gates (figures 7 and 8). Diagnostic messages assist the user in identifying potential design flaws. The combined geometries of the castings

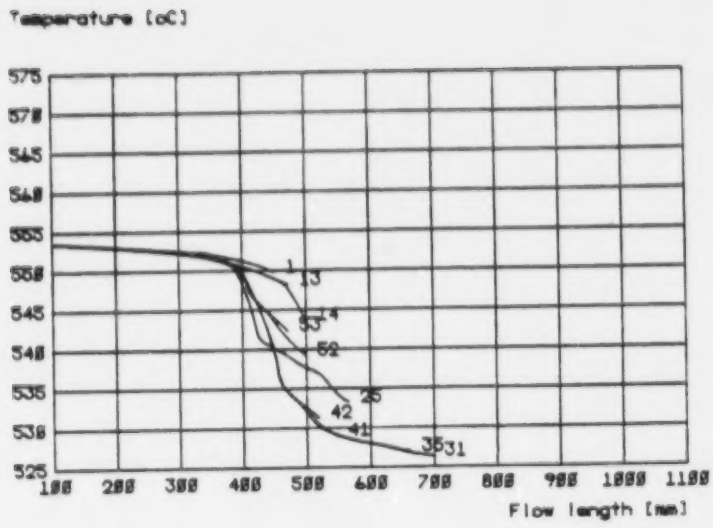

Fig. 6: Temperature drop results from filling simulation

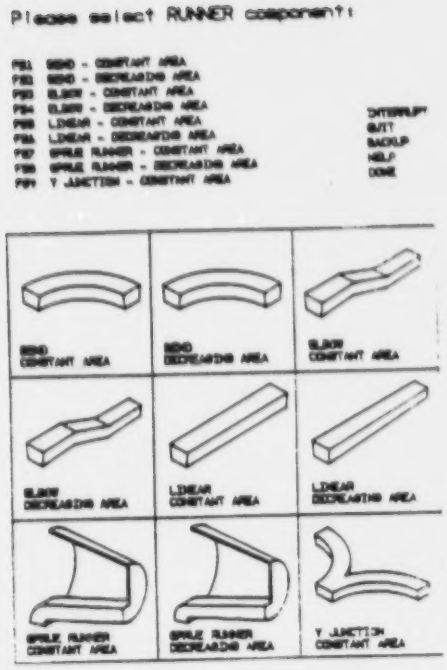

Fig. 7: Graphic menu for selection of runner component

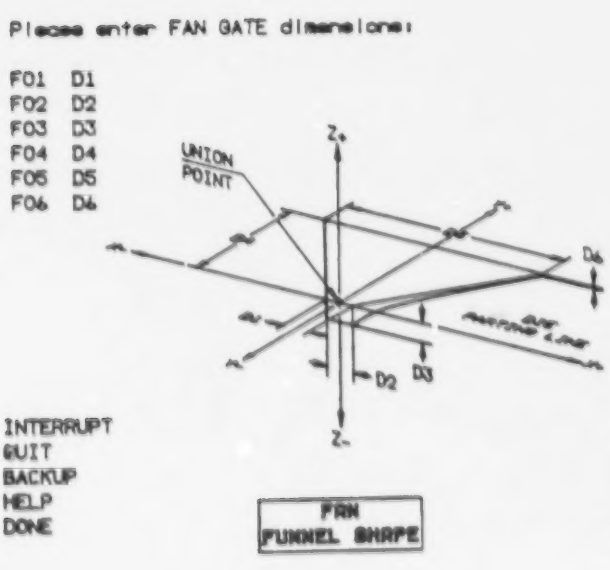

Fig. 8: Graphic menu using a parametric design

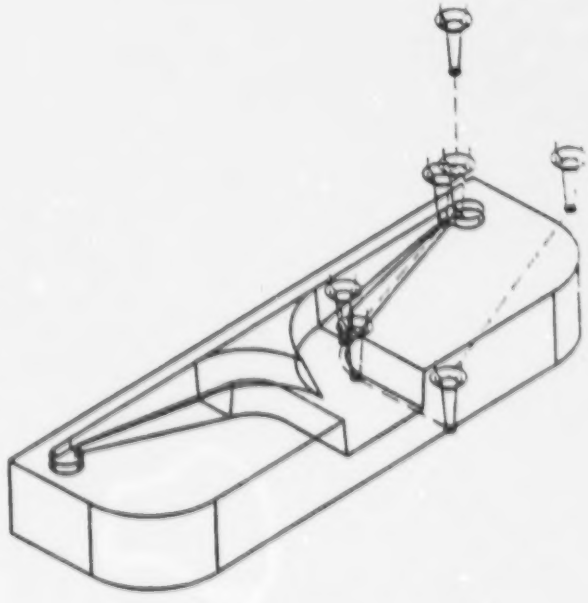

Fig. 9: CNC machining-tool path generation

with the feeding system can then be used in balancing multicavity systems and for evaluation of shot size or percentage of remelt. The stored geometrical data are also used for die design and for the CNC toolpath generation (figure 9). The overall die dimensions are established considering the effects of the casting pressures and the permissible die deflections. The cooling requirements of the die and the product are analyzed and the cooling system is designed.

During the analyses, the system provides a guidance by supplying recommended processing conditions, such as melt characteristics, die temperature, filling time, gate velocities and injection pressure. The designer chooses practical values to start the analysis and receives appropriate messages if the results are not within the acceptable limits.

DESIGN OPTIMIZATION BY PRODUCT PERFORMANCE ANALYSIS

Having optimized the product design and the processing parameters, a detailed analysis of the product service performance may be required. The interactive mechanical analysis routines can be first employed in rapid evaluation of the effects of forces during casting and ejection as well as in making approximative analyses of the behavior under the service load conditions. To complete the design optimization, a finite element procedure may be required for important parts. Taking an advantage of the integrated approach it employs the non-uniform material properties as predicted during die filling and cooling analyses.

CONCLUSIONS

New simulation capabilities can be achieved by integration of the die casting technologies together with solid modeling, finite element method, and all required material databases. The incorporated procedures address every aspect of the product development cycle giving the user an important advantage over the past practice of relying on partial solutions.

The implementation of this technology can significantly improve the design and manufacturing efficiency and the flow of information during the product development cycle. The integrated system offers the user the capabilities of an overall optimization of the product, the production process and the tool design by bringing together all the applicable simulation capabilities such as filling analysis, cooling analysis, mechanical analysis, solid modeling and material engineering.

ON THE COMPUTER SIMULATION OF METAL FORMING PROCESSES

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ABSTRACT

In this paper, the utilization of the finite element method for modelling a variety of non-isothermal metal forming processes is discussed. Applications covered are the compression of an aluminium cylinder, extrusion, hot rolling and hot forging.

RÉSUMÉ

Cet article traite de l'utilisation de la méthode des éléments finis pour la modélisation des procédés non-isothermes de mise en forme des métaux. Les exemples traités portent sur le forgeage à chaud, le laminage à chaud, l'extrusion et une opération de refoulement simple.

INTRODUCTION

Due to the complex nature of both the materials and the processes involved, forming technology has relied heavily upon the accumulated experience of trial-and-error methods. The theories used for the design of process schedules and forming tools, were derived from oversimplified assumptions. While these methods have contributed significantly towards the forming technology, they are unavoidably wasteful in material and energy, and hence expensive. In the recent years, the forming industry has been faced with the challenge to provide high quality, high precision and low cost products. It is therefore imperative that efficient methods for the design of process schedules and forming tools be developed and used by Canadian forming industries.

Only recently, the finite element method [1] has gained significant recognition in the field of metal forming. In fact this method is the only method that is capable of dealing efficiently with the complex geometries of the workpiece and tools, and with the continuously varying boundary conditions typical of forming problems. The finite element method considers a continuum as an assembly of subdomains or finite elements. Each element can have specific physical properties which can be varied with process conditions. This capability to account for the continuously changing mechanical properties makes it desirable in the analysis of unsteady forming processes, and in situations where the deformation history plays a

dominating role in the material strength and workability of the final product. The method, if used in conjunction with CAD/CAM techniques, should offer the most complete information necessary for process scheduling, forming tool design and production control.

In this paper, the application of FEM to a variety of metal forming processes such as upsetting, extrusion, rolling and forging will be discussed. The analyses for the upsetting, the extrusion and the rolling were carried out using the coupled thermomechanical model, METFORM, which has been developed in-house at MTL/CANMET. METFORM can handle all metal forming problems including casting analyses. For the forging operation, the analysis was performed using the ALPID software developed at Battelle Laboratories and installed on the CAD/CAM system at IMRI. ALPID is a user oriented package particularly suited for analyzing forging operations. Both programs are based on a viscoplastic theory using FEM method [2-4]. They have the capability of simulating the deformation behavior of metals and its accompanied heat transfer phenomena, as well as the heat production due to plastic energy dissipation. They can handle 2D and axisymmetric problems.

UPSETTING: Upsetting is the simplest form of forging. It is also the most commonly used method for evaluating the mechanical properties of metal during forming processes. Here, the compression of an aluminium cylinder, at room temperature, under a strain rate of 20 sec-1, is considered in Figure 1. Due to the symmetry of the problem, only one quarter of the cylinder needs to be analyzed. In the present simulation, 2 extreme cases are considered: fully lubricated and fully restrained end conditions. Corresponding experiments were performed for model verification [5]. Figure 1.a shows an excellent agreement between the stress/strain curve predicted by METFORM in the fully lubricated condition and the corresponding experimental results. Figure 1.b compares the predicted deformation profiles with experiments conducted in a fully constrained condition. Again excellent agreement is self evident. It is noteworth that the predicted temperature rise at the center of the cylinder due to plastic energy dissipation is 314.4 C and the measured value is 313.6 C. The closeness between the two values is expected due to the fact that the process was so rapid that the short duration of the deformation did not permit heat transfer to occur. For more complex situations, the correct prediction will have to rely upon the accurate knowledge of the heat transfer coefficient at the interfaces and the thermophysical properties of the material being processed. Figure 1.c shows the predicted effective strains. Experimental attempts were made to measure the local interior strain variations but failed. This illustrates how the model can provide local detailed information while this information is either inaccessible or difficult to obtain experimentally.

EXTRUSION: The extrusion problem to be considered here, consisted of a top die and a bottom die with the geometrical configuration shown in Figure 2.a. Experiments were performed using plasticine as a model material. Rectangular grids were scribed on the surface for measuring the deformation field. This problem was simulated using a visco-plastic model [6]. Figure 2.b shows both the predicted and experimental results. The effective strain contours at a 30% reduction are shown in Figure 2.c. It is worth noting that the strain is highly localized in areas where shear

is dominating the flow of material. This is indeed the areas where shear band formation occurs in practice.

ROLLING: In industrial hot rolling, the slabs to be rolled are preheated in a reheating furnace. These slabs are placed on water cooled rails (or skids) during reheating. The temperature is significantly lower at locations where the slabs are in contact with the skids because of shading and cooling effects. The cold spots, known as skid marks, have a significant influence on the flow behavior during rolling and on the mechanical properties of the rolled products.

Here, a hypothetical case is investigated. The non uniform temperature distribution shown in Figure 3.a, represents the assumed initial temperature for a portion of the slab. One rolling pass is considered. Figure 3.b shows the temperature distribution at the end of the pass. The velocity field calculated, reveals differences between the top and the bottom surfaces of the slab. This is indeed an expected phenomenon due to skid marks and it is frequently observed in industrial rolling operations. This phenomenon is known as the "head-down-turn" exhibited in roughing processes. It can cause substantial damage to the run-out table. The METFORM model offers here a useful tool for investigating this phenomenon and improving the process.

Figures 3.c and 3.d show the effective strain distribution at the beginning and at the end of the pass. The steep strain gradients across the thickness of the slab and the inhomogeneous strain distribution due to a non-uniform temperature is certainly worth noting. These factors could cause varied accumulation of history effects and microstructural development and thus affect the final mechanical properties of the rolled products. Such information, which is invaluable for the design of rolling schedules is not obtainable by any other experimental means.

FORGING: Results have been obtained from the simulation of the two first of five forging operations required to forge a railway car steel wheel. Slugs of a steel similar to AISI 1060, 16 in. dia x 18 in. are first flattened down to a slab of 6 inches in height. The initial forging temperature is 1220°C. Slabbing is followed by a forging operation which distributes the material to form the hub, the wheel plate and the rim part of the wheel. These two preforming operations are performed on a single hydraulic press, the two sets of dies being mounted on sliding tables. A punching operation makes the bore, a rolling operation increases the ring diameter and forms the flange of the wheel. Finally a dishing operation is used to position the hub with respect to the rim and to give the wheel plate its final shape.

Figure 4 illustrates some of the results obtained from a finite element simulation of the first two operations with ALPID. It solves the heat transfer and the non isothermal deformation problems. For the latter case, deformation and temperature are solved alternatively for each stroke increment [7], the friction work and a fraction of the plastic work (90%) being transformed into heat.

Figure 4.a illustrates the deformation at the end of the slabbing operation. The extensive side folding effect which is observed is related to

the cooling of the end faces, the initial temperature of the dies being 300°C. The temperatures calculated at the end of the slabbing operation are shown in Figure 4.b. While the die sets are being exchanged, the workpiece is waiting on a side table and temperature changes are taking place. Heat is lost by conduction into the table, and by convection and radiation into the environment. Figure 4.c shows the temperatures at the end of this idle period. It can be seen that temperature has been considerably homogenized near the top surface of the slab, but cooling is still strong in the lower part of the slab.

In the second forging operation, the shape must be forged with no flash. Maps of the node velocity vectors are used to get a clear picture of the deformation process during this second operation. Figure 4.d shows the node velocity vectors at an intermediate stage during the second operation. In Figure 4.e, it can be seen that the flash has started to form while the cavity is just about to be filled. Strain contours give additional information on the process. The mechanical history of any interesting point can be obtained from post-processing.

The temperatures in the dies which are assumed to be initially at 300°C, are also obtained. Temperature results are shown in figure 4.f. These temperatures can be used in conjonction with the values of forces at each node of the workpiece contour to calculate the stresses in each die using standard FEM elastic analysis.

CONCLUSIONS

In these numerical models, the most important parameters with regard to the deformation behavior of the workpiece are the material flow stress, the friction and the heat transfer at the tool-metal interfaces. In most metal forming processes, flow stress values have to be known over a relatively large range of temperature and strain. Although extensive data on metal flow stress have been compiled [8], a great variability can be found between the sources of information. Compression tests with the actual material and covering the full range of conditions encountered in the process are used to establish the flow stress equations. In sequences of hot forming operations, metallurgical transformations are likely to occur between operations and affect the flow stress values for the subsequent operation. Multi-strike compression tests can be used to assess the effects.

Friction is a function of the pressure, the nature of the lubricant and the local deformation. For the above studies, either a uniform friction shear factor or a function dependent relation has been assumed at each tool-metal interface. Heat transfer also depends on numerous factors; pressure, nature of lubricant, amount of oxide, etc. A simple heat transfer coefficient is used to represent this complex phenomenon. Experience and experimental verifications are then necessary to precisely model these parameters.

In the above, we have demonstrated the capability of the FEM simulation in the modeling of a variety of metal forming processes. The simulations revealed information which was intangible by any other means, including time consuming and costly experimental techniques. The predictability of

temperature flow velocity, and strain/stress distribution in the workpiece and at the tool/workpiece interface offers a better understanding of the cause of tool damage; and thus leads to better design of tools and process schedules, improved surface quality control and minimal tool damage.

It is well recognized that micro-structural development is a strong function of deformation, strain rate, strain and temperature. The models' capability to predict these parameters thus offers the important link for the study of microstructure formation. This in turn leads to effective control of mechanical properties of the formed products. Reduction of both the rejection rate and the cost should follow.

REFERENCES

[1] Zienkiewicz O.C., The Finite Element Method, McGraw Hill, 1977

[2] Zienkiewicz O.C., Onate E., Heinrich J.C., Plastic flow in metal forming - I Coupled thermal behavior in extrusion. Appl. Num. Meth. Form. Proc. ASME AMD 28 (1978), 107-120.

[3] Rebelo N., Kobayashi S., A coupled analysis of viscoplastic deformation and heat transfer, 1 Theoretical considerations, Int. J. Mech. Sci., Vol. 22, pp 699, 1980

[4] Zienkiewicz O.C., Nakazawa N., Vilotte J.P., Finite element in forming processes, Advanced Technology of plasticity, Vol 2, 1984, Proc. 1st Int. Conf. on Technology of Plasticity, Tokyo, Japan.

[5] Too J.J.M., Baragar D., A coupled thermomechanical model for metal forming processes - The experimental verification, PMRL 87/77(TR), 1987

[6] Biner S.B., Harneas J., Too J.J.M., An analysis of axisymmetric extrusion with numerical and model material techniques, Proc. of the Int. Symp. on computer modelling of fabrication processes and constitutive behavior of metals, Ed. J.J.M. Too, May 1986, Ottawa

[7] Wu W.T., Oh S.I., ALPIDT: A general purpose FEM code for simulation of non isothermal forming processes, Proc. 13th NAMRC, 1985, pp 449

[8] Altan T., Boulger F.W., Flow stress of metals and its application in metal forming analysis, ASME Trans., J of Eng for Industry, Nov. 1973, pp 1009

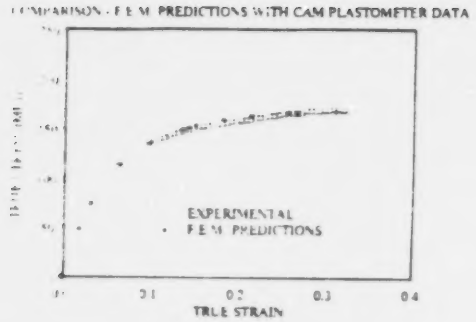


Fig. 7: Prediction of Stress/Strain Behavior on a Homogeneously Deformed Cylinder Under Compression.

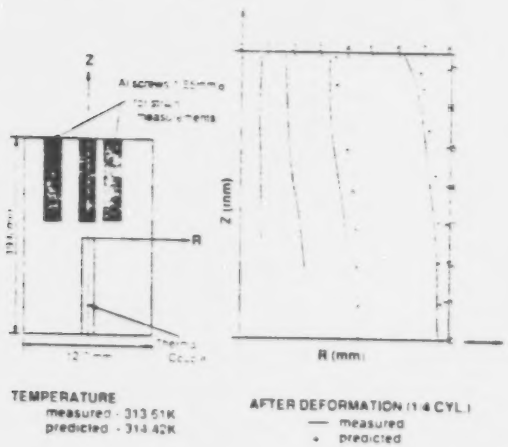


Fig. 8: Prediction of Inhomogeneous Deformation of a Cylinder Under Compression.

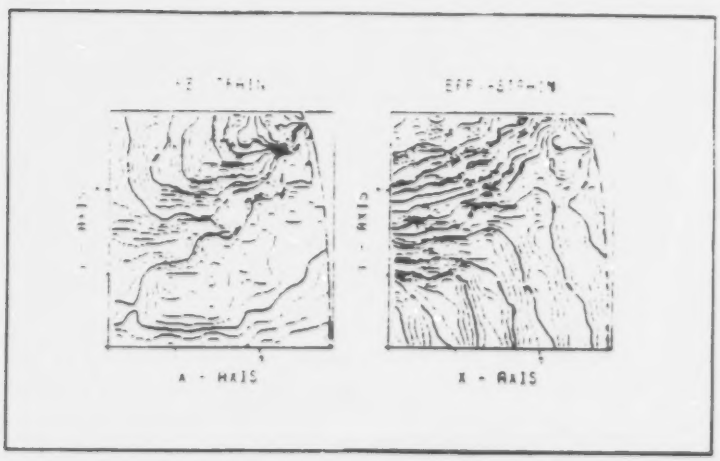


Fig. 9: Predicted Effective Plastic Strain Contours.

Fig. 2a

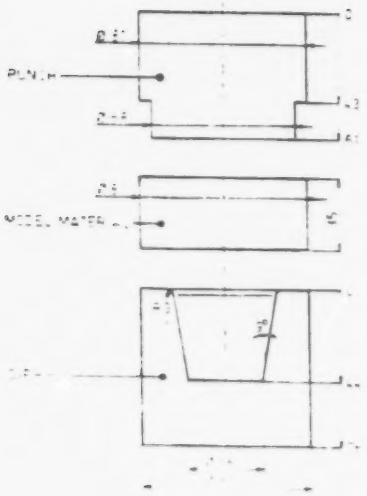
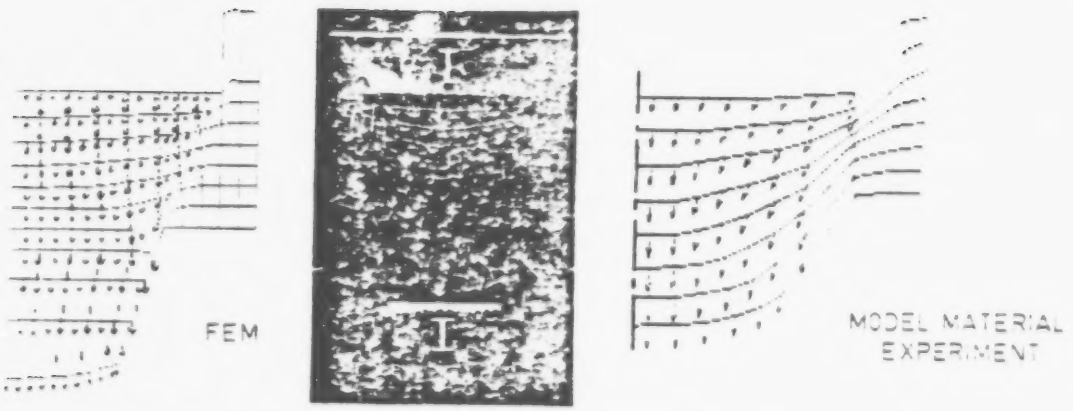
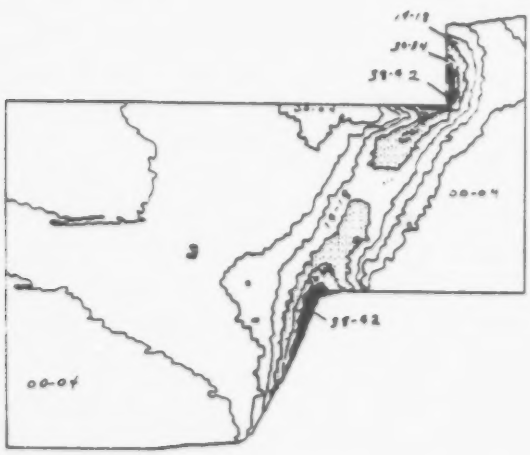


Fig. 2b



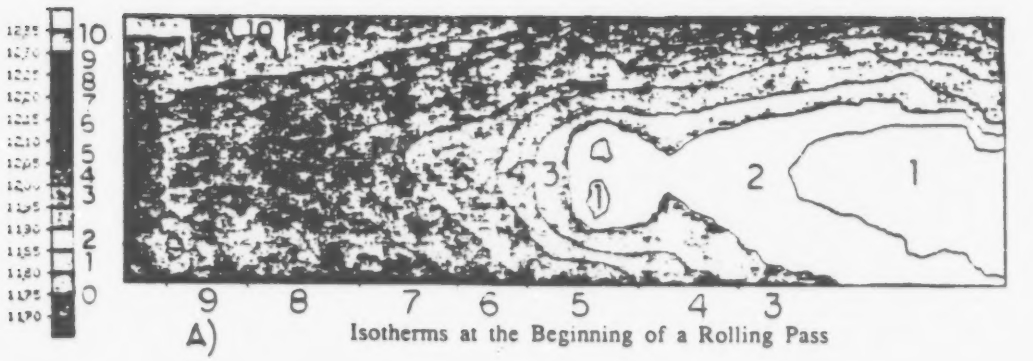
Velocity fields calculated by FEM and from wax experiments for 30% reduction.

Fig. 2c

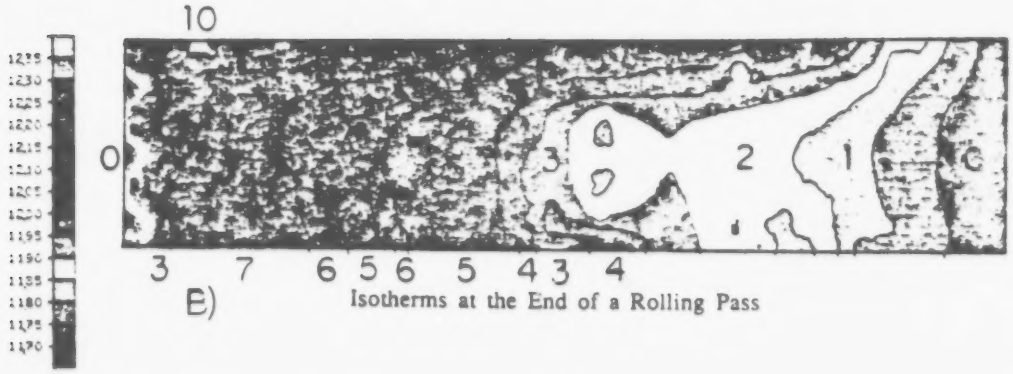


Effective plastic strain distribution obtained from FEM at 30% reduction.

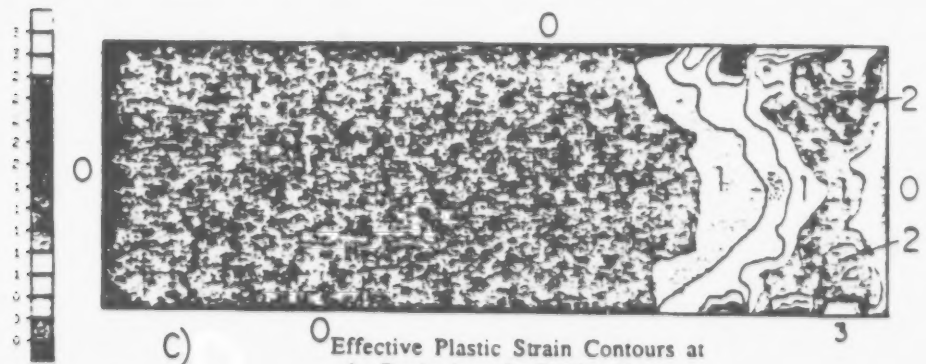
Figure 2: Modeling of axisymmetric extrusion



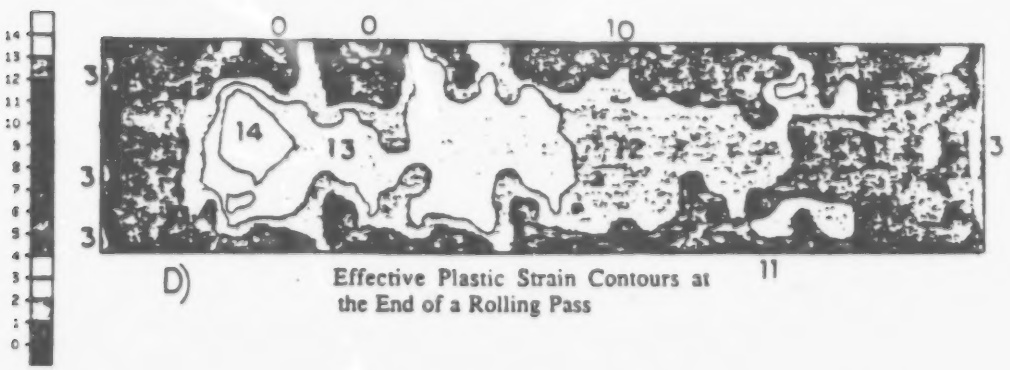
A) Isotherms at the Beginning of a Rolling Pass



E) Isotherms at the End of a Rolling Pass

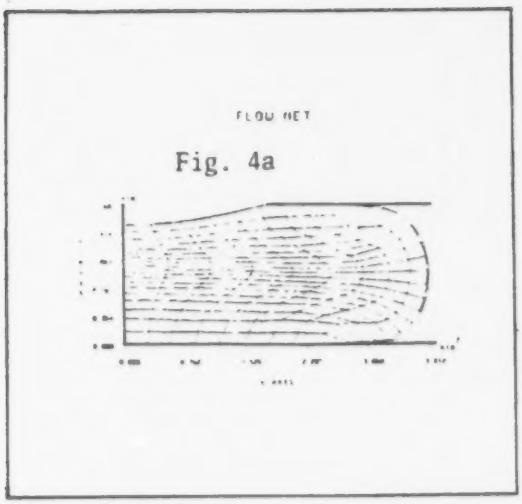


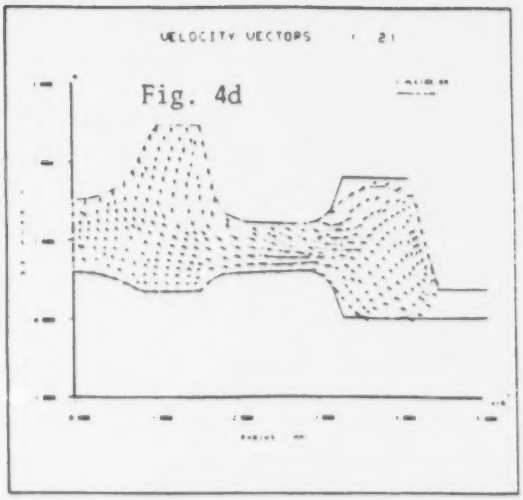
C) Effective Plastic Strain Contours at the Beginning of a Rolling Pass

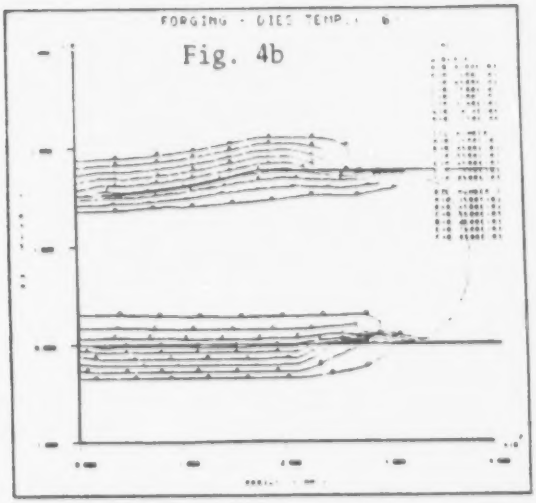


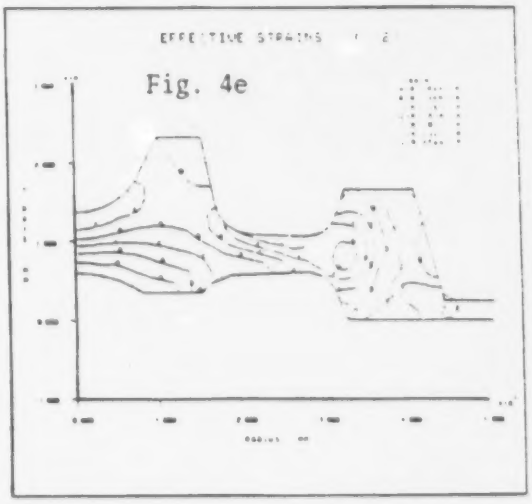
D) Effective Plastic Strain Contours at the End of a Rolling Pass

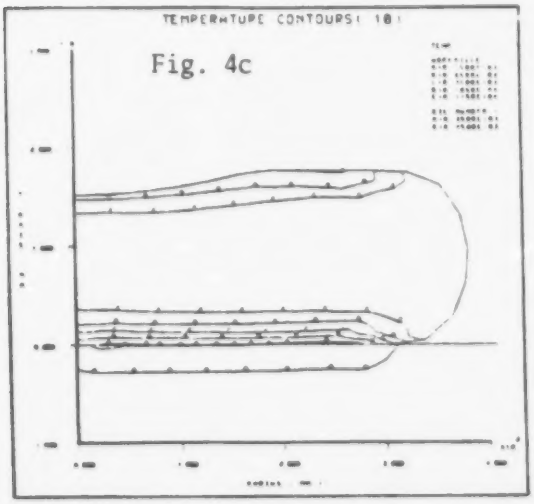
Fig. 3 Results of the hot rolling simulation.











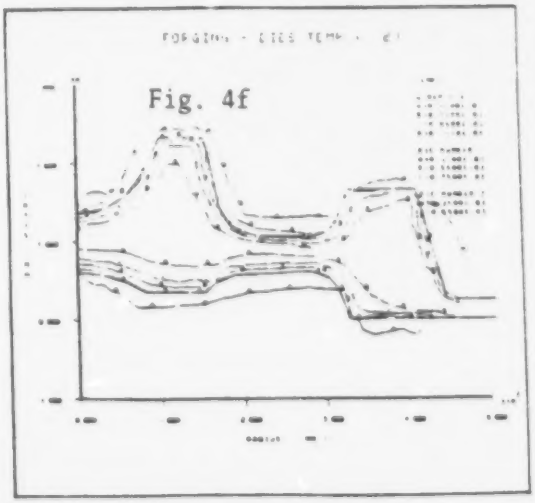


Figure 4: Simulation of the forging of a rail car steel wheel

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SESSION 4

CIMP and Manufacturing Technologies
/ SIMM et les industries manufacturiéres

Chairperson/ Modérateur : J. Scrimgeour

Senior Adviser, CAD/CAM, Robotics and Industrial Automation, Division of Electrical Engineering /NRC

conseiller sénior, CAO/FAO, robotique et automatisation industrielle, division de génie électrique /CNRC

INSTITUT FÜR KUNSTSTOFFVERARBEITUNG
in Industrie und Handwerk an der Rhein.-Westf. Technischen Hochschule Aachen

LEHRSTUHL
FÜR KUNSTSTOFFVERARBEITUNG
PROF.DR.-ING. G. MENGES

STIFTUNGSPROFESSUR DES STIFTERVERBANDES
FÜR DIE DEUTSCHE WISSENSCHAFT
PROF.DR.-ING. W. MICHAELI

"CIM and Plastics Processing"

E. Baur

W. Michaeli

G. Menges

Aachen, July 1988

For various reasons, the plastics processing industry is very innovative in the field of computer-integrated manufacturing.

One of the main reasons for this is almost certainly the complex relationship between material, part geometry and processing parameters which influences the properties of the final plastic parts. Without the use of advanced computer programs, these relationships cannot be sufficiently well defined.

The most important method of plastics processing is injection moulding which permits efficient processing of various polymers with a degree of design freedom right up to complex geometric figures with ribbed outer surfaces.

At the same time it is important to remember that in this method, two fundamentally different manufacturing processes are combined, namely the production of the metal mould and then the processing of the plastic using this mould.

Computer-integrated system solutions in injection moulding shops must therefore integrate the computer-aided design and manufacturing methods of the metalworking industry into the general concept for plastics moulding.

Material Selection

With polymers, the selection of the most suitable material is a complicated problem. The engineer has the choice from thousands of different types of plastics on the market which, in turn, can be further modified by the use of a wide range of filler or by blending. The spectrum of properties for plastics ranges from material to material far more widely than for the classical construction materials with which we are familiar. In addition to the mechanical properties, the interactions of a variety of other factors such as optical, rheological, thermal, electrical and chemical properties also have to be taken into consideration before a final decision can be taken on the use of a particular material.

An additional problem is the fact that the mechanical properties in particular cannot be regarded as constant, since they are very heavily dependent on various other parameters such as temperature and time. They can also be influenced to a great extent by the processing conditions.

A material data base adapted to the special properties of these materials is the basic precondition for any design work.

It is therefore not surprising that a vast range of material data bases is already available either on-line or on floppy disk /1, 2, 3/. One particularly notable example of such data bases is a system which has been produced by a number of European raw materials producers who not only use uniform data formats, but who also determine the material data using strictly standardized test procedures, so that genuinely comparable values are now available for the first time /4/.

At the IKV, a material data base was developed which serves as a framework for the management of polymer material data /5/. The user can determine which materials are stored in the file with which characteristics. As a result, each company is responsible for its own data maintenance, but can also incorporate internal data.

A further feature of this system is the centralized incorporation into a computer-aided engineering (CAE) environment which allows any program access to the necessary material information at any time (Fig. 1). For properties subject to function relationships, it is possible to draw on the corresponding functional sequences.

Part Design

Part design using CAD can be regarded today as the state of the art. The next important step must be to ensure that material and process-specific characteristics are also incorporated into these systems.

"Macro" programs can be used, for example, to design frequently used functional elements at the push of a button. The results of the calculations are then available not only in numerical form; they also provide the geometry and plastics-oriented design of the functional element calculated in the CAD system.

The extent to which the subsequent processing must be taken into consideration at the part design stage is illustrated by the fact that one of the most important macro programs is used to design gating systems. This program can be used for determining the geometry of the gates and runners, as well as generating the FE mesh required for the filling simulation (Fig. 2 and 3).

If the part geometry or loading become too complicated, the conventional methods of calculation must be abandoned in favour of the finite elements method (FEM).

During mechanical analysis and structure optimization using FE computer programs, the generally inhomogeneous, anisotropic and non-linear material behaviour of plastics can be numerically approximated. Measurement of the necessary material properties for non-linear analyses is extremely cost-intensive and time-consuming. When compared with the construction of prototypes, however, savings in time and costs can be achieved particularly where changes in design and/or parameter studies are required /6/.

Today, mechanical models are available with which all three major loading situations (impact, short-term and long-term loading) can be controlled.

Mould Design

Computer applications in this area are focussed on the technical optimization of the injection moulding process, for which a wide range of filling simulation programs are already available /7, 8, 9/.

The CADMOULD-MEPHISTO program, for example, incorporates programs /6/

- For calculating the temporal melt front advance and pressure distribution during the mould filling phase (Fig. 4),
- For calculating the shear rates, shear stresses and melt temperatures along freely selected flow paths,
- For determining the most favourable machine operating point and its dependence on operating parameters, and
- For analysis of the holding pressure phase and estimation of the shrinkage.

The results of these simulations allow the welding lines, air bubbles and, using the temporal curve of the velocity vectors (Fig. 5), the molecular and fibre orientations to be derived.

Using this type of simulation program, the designer is able to recognize the most appropriate (from the point of view of part quality and productivity) method of gating the moulding to the runner system. Furthermore, the simulation of the filling process provides information on the thermal and mechanical loads to which the material is subjected during moulding. Damage to the material due to excessive stresses during processing can thus be avoided. Without the use of simulation programs, this could only be assured subsequently through time-consuming and cost-intensive experiments on the processing machine.

Since, due to their macro-molecular structure, plastics always have the ability to develop anisotropic properties whose extent depends on the loading exposure during processing, it is only through the use of computer programs that such anisotropies are able to be either prevented or deliberately exploited with the aim of achieving savings in material and weight /10, 11/. This applies in particular to the technical plastics filled with chopped strands where a particularly favourable material behaviour can only be achieved in the direction of fibre orientation.

Transfer of NC Data

A process-oriented mould design using process simulation always entails the optimization of the process itself, and thus a determination of the most favourable machine settings. These are available for direct transfer to the controller of the injection moulding machine or on appropriate data carriers.

One major problem here is the lack of standardized interfaces for machines from different manufacturers /12/. This has resulted in only individual solutions being possible to date.

The state of the art, however, is the transfer of geometric data from the CAD system to NC programming systems.

The contour of the shaped mould insert can be used to determine the geometry of the spark erosion electrode required for production of the mould. Using the electrode as a model, it is now possible to plan the milling process, and to pass on the information in the form of NC data to the processing machine on which the electrode is then automatically produced.

Flexible Manufacturing Systems in Injection Moulding Shops

The modern injection moulding shop must today organize its manufacturing process so flexibly that it can produce small batches of various mouldings with the smallest possible storage and with minimum time and material losses, thus reducing capital outlay and storage costs, but at the same time being able to react to demand at short notice.

In order to achieve this, manufacturing facilities are required which allow the production to be changed within a short space of time. In principle, the modern injection moulding machines with their microprocessor-based controllers are suitable for such applications. In practice, however, a wide range of peripheral facilities are also required which, as far as the wide range of

products is concerned, are equally as versatile as the injection moulding machines, which permit fully automated production and also facilitate the rapid change-over of all the article-specific production facilities.

These are /13/:

- Mould changing facilities for the injection moulding machines (including the quick-action mounting and coupling facilities),
- Mould transport facilities,
- Mould preheating stations,
- Flexible handling systems, in particular robots, also with interchangeable grippers),
- Raw material feeder facilities,
- Finished product transport systems or handling systems for linking to subsequent production stages.

At the IKV, a flexible manufacturing centre (Fig. 6) was developed which requires low investment costs, and at the same time also allows composite mouldings to be produced from thermoplastics or rubbers of reproducibly high quality from the very first moulding. This manufacturing cell incorporates two injection moulding machines, each with their own mould changing system. A mobile 5-axis industrial robot performs not only the handling tasks such as demoulding or feeding the rubber machine with the previously injection moulded inserts, but is also used for the assembly of several parts to form modules. For this purpose, the robot has automatically replaceable grippers and assembly tools. The robot also forms the link to the subsequent production.

The interactions of all the components in the manufacturing cell are coordinated and monitored by a cell computer. At each change of production, the cell computer transfers the article-specific parameter sets to the machines.

In a reverse process, information on the production process flows from the cell computer to the production control computer which can then process these data for various forms of documentation.

Computer-Integrated Manufacturing for Fibre Composites

Although injection moulding is the classical area of application for computer-integrated manufacturing in the plastics industry, a number of promising steps have already been taken in the field of fibre composites, two of which are described briefly below:

Simulation of Filament Winding

The development of composite parts can only be carried out if done in close cooperation with production engineering. A CAD/CAM system for filament winding must be able to consider practical constructive steps which are considered feasible.

The first step in the simulation of filament winding is to produce the winding core geometry with the help of a frame model. Certain geometries like solids of revolution and prisms can be called up from storage and assembled into a final geometry. In order to arrive at a windable part geometry, several variations of the cores are possible.

When producing the laminate structure and winding the core, one is restricted to guiding the rovings over non-skid tracks. The placing of the roving is calculated step-by-step as the path goes in a straight line over the part surface, and changing directions only in surface interfaces (Fig. 7) /14/.

Simulation of the Compression Moulding Process of SMC

The material properties of sheet moulding compound parts (SMC) are determined by fibre orientations and knit line formation produced during pressing. Programs to simulate the mould filling process can reduce the costs in the early development of part and mould geometries. Results from such simulations are the flow pattern during pressing, fibre orientation of the final parts, mechanical loading of the mould and position of the knit lines. These results can be used by the designer to dimension the parts. The fibre orientation which results from the process simulation can then be taken to calculate the stiffness and strength of a part. This simulation is used for the mould filling process of thermoset SMC charges as well as for the flow of fibre-reinforced thermoplastic charges such as GMT /14, 15/.

References

/1/ Baur, E.
Werkstoffdatenbanken für den Konstrukteur
Kunststoffberater 33 (1988) 1/2
p. 31 - 36

/2/ Hassel, A.
Material Databanks Boost Designers Efficiency
machine design, April 1986

/3/ N.N.
let a computer select the right material
modern plastics international 15 (1985) 8, p. 29 - 30

/4/ Schmitz, J.
Oberbach, K.
Material Properties for Database - An Offer of the Raw Material Suppliers
46th ANTEC, Atlanta, April 18 - 21, 1988

/5/ Baur, E.
Menges, G.
The material data bank - a central part of a CAE program to assist the designer of plastic components
45th ANTEC, Los Angeles, May 4 - 7, 1987

/6/ Menges, G.
Michaeli, W.
Baur, E.
Lessenich, V.
Schwenzer, C.
Computer-Aided Plastic Parts Design for Injection Moulding
Materials '88, May 9 - 13, 1988, London

/7/ Hoven-Nievelstein, W.B.
Der Einsatz von Rechenhilfsmitteln bei der Konstruktion von Spritzgießwerkzeugen
Kunststoffe 75 (1985) 12, p. 866 - 877

/8/ Austin, C.
Vergleich von Fließalgorithmen
Moldflow, Ltd.

/9/ Thienel, P.
Berlin, R.
Flexible Fertigung mit CIM und CAE im Spritzgießbetrieb
Kunststoffe 77 (1987) 2, p. 188 - 193

/10/ Austin, C.
Predicting Mechanical Properties of Injection Molded Parts from Computer Analysis
46th ANTEC, Atlanta, April 18 - 21, 1988

/11/ Mahlke, M.
Osswald, T.A.
Ott, S.
Specker, O.
Thieltges, H.P.
Wölfel, U.
Spritzgießen und Pressen verstärkter Kunststoffe
14. Kunststofftechnisches Kolloquium
Aachen, March 9 - 11, 1988
Proceedings p. 335 - 366

/12/ Spamer, P.
Hoven-Nievelstein, W.B.
u.a.
Flexibles Fertigungszentrum für das Spritzgießen kleiner Serien
Kunststoffe 74 (1984) 9

/13/ Menges, G.
Benfer, W.
Baur, E.
CIM in der Spritzgießtechnik - Werkzeugentwicklung und Fertigung
ZwF 82 (1987) 6, p. 311 - 316

/14/ Menges, G.
Effing, M.
CADFIBER - A Program System for Design and Production of Composite Parts
Proceedings of the SPI/CI
43rd Annual Conference

/15/ Osswald, T.A.
Numerical Methods for Compression Mold Filling Simulation
Doctor thesis, 1986, University of Illinois at Urbana Champaign/USA

Figures

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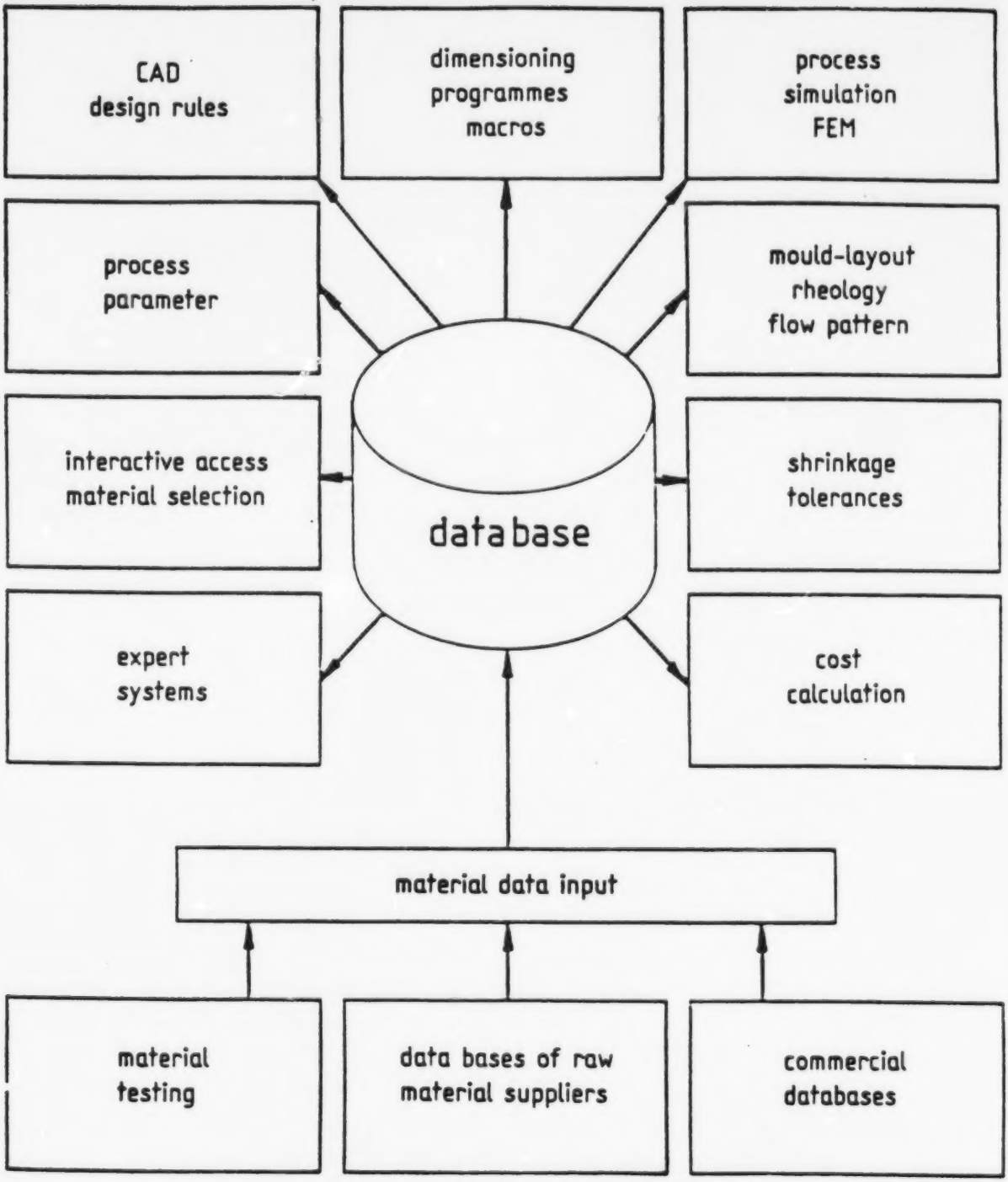
2. Runner system (solid model)
3. Runner system (FE-mesh)
4. Filling simulation
5. Temporal velocity vectors
6. Flexible manufacturing centre
7. Simulation of filament winding



Database in the CAE-context

Figure 1

WARTEZUSTAND

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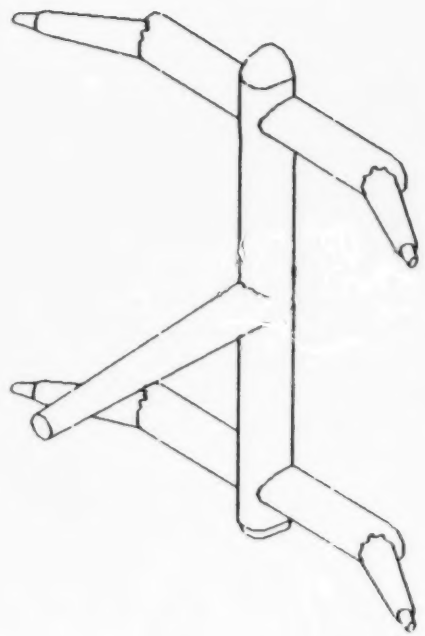


Figure 2

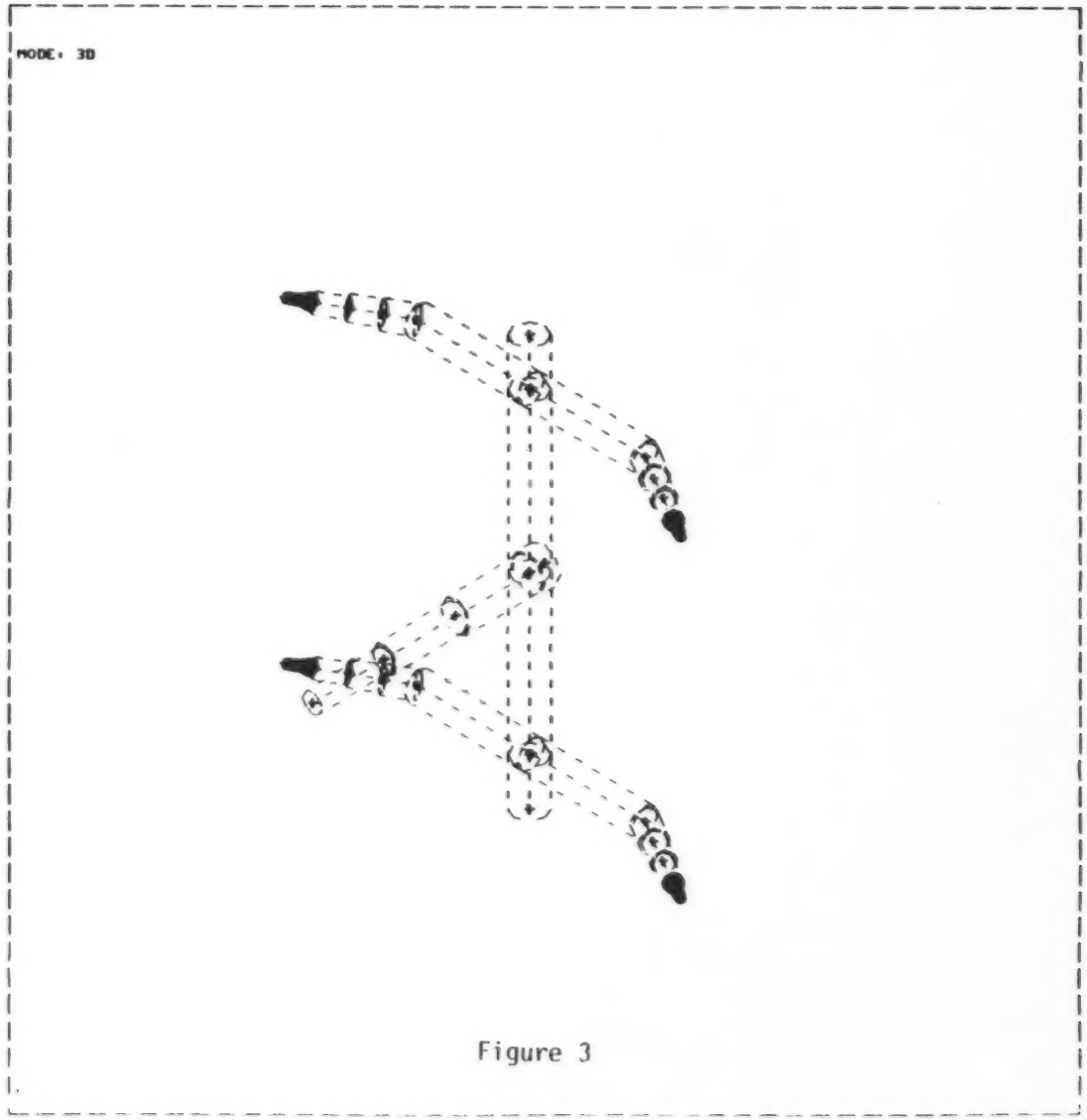
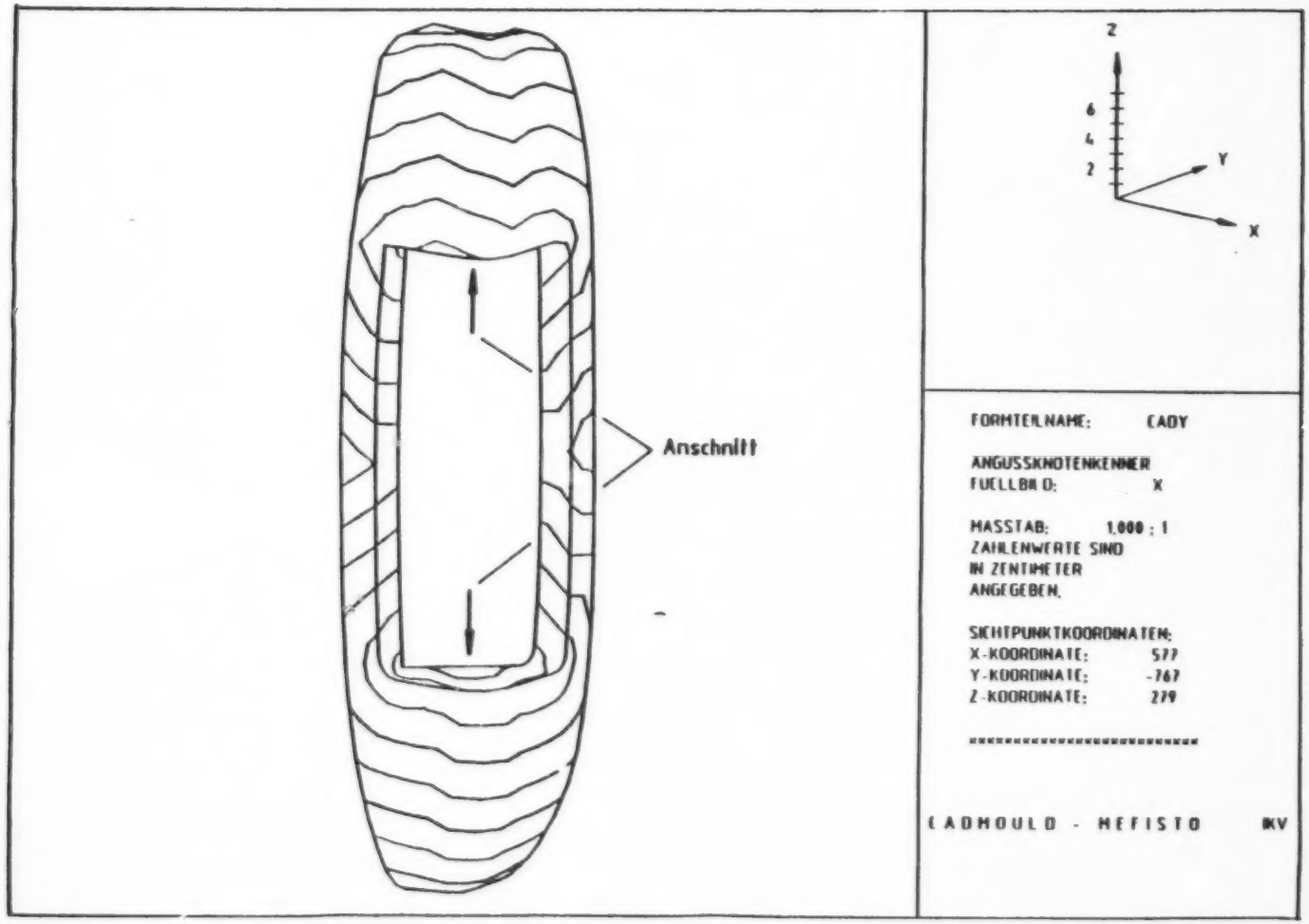


Figure 3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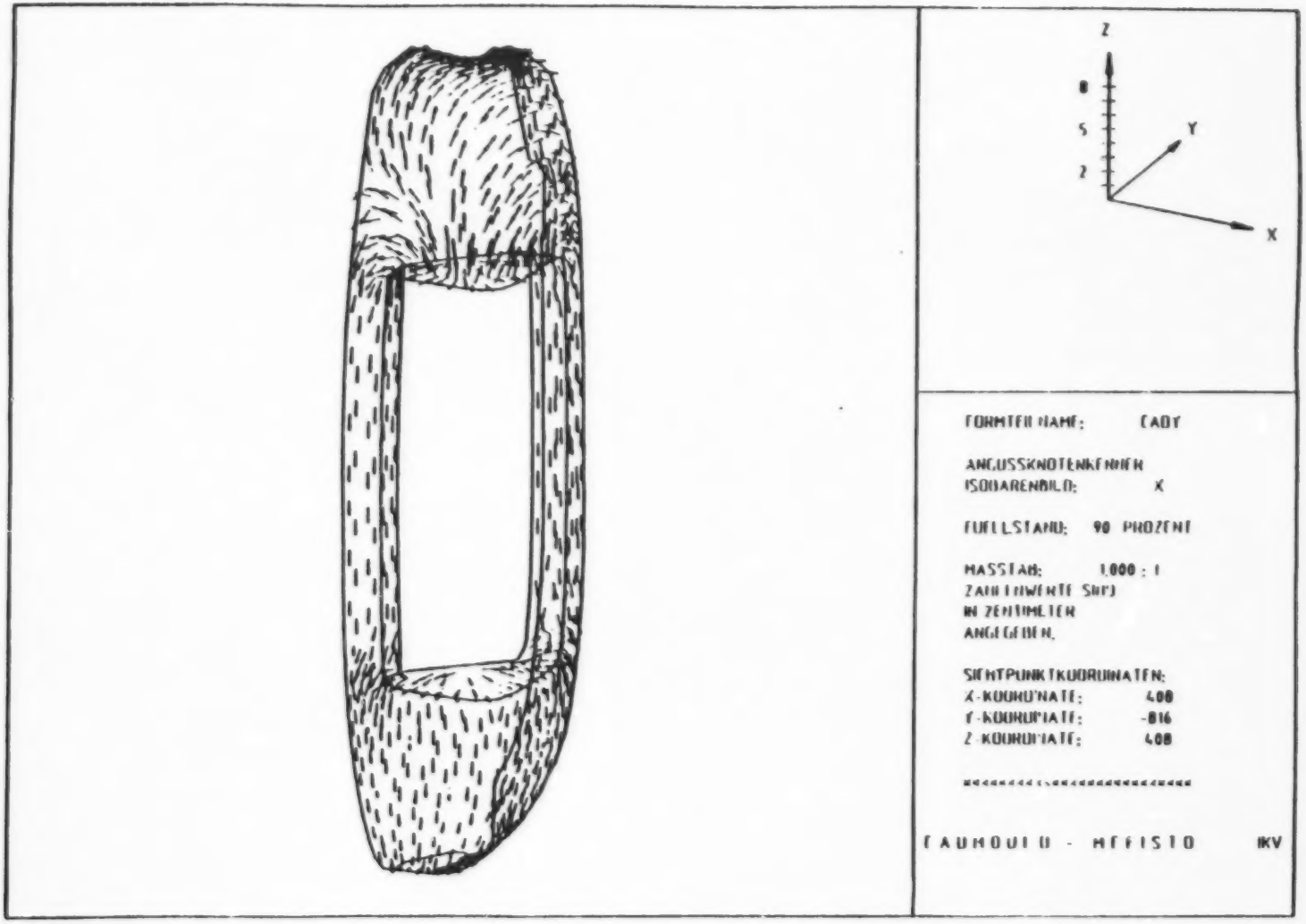
CADMOULD - MEFISTO BV

Figure 4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CAUMOULD - MEFISTO
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Figure 5

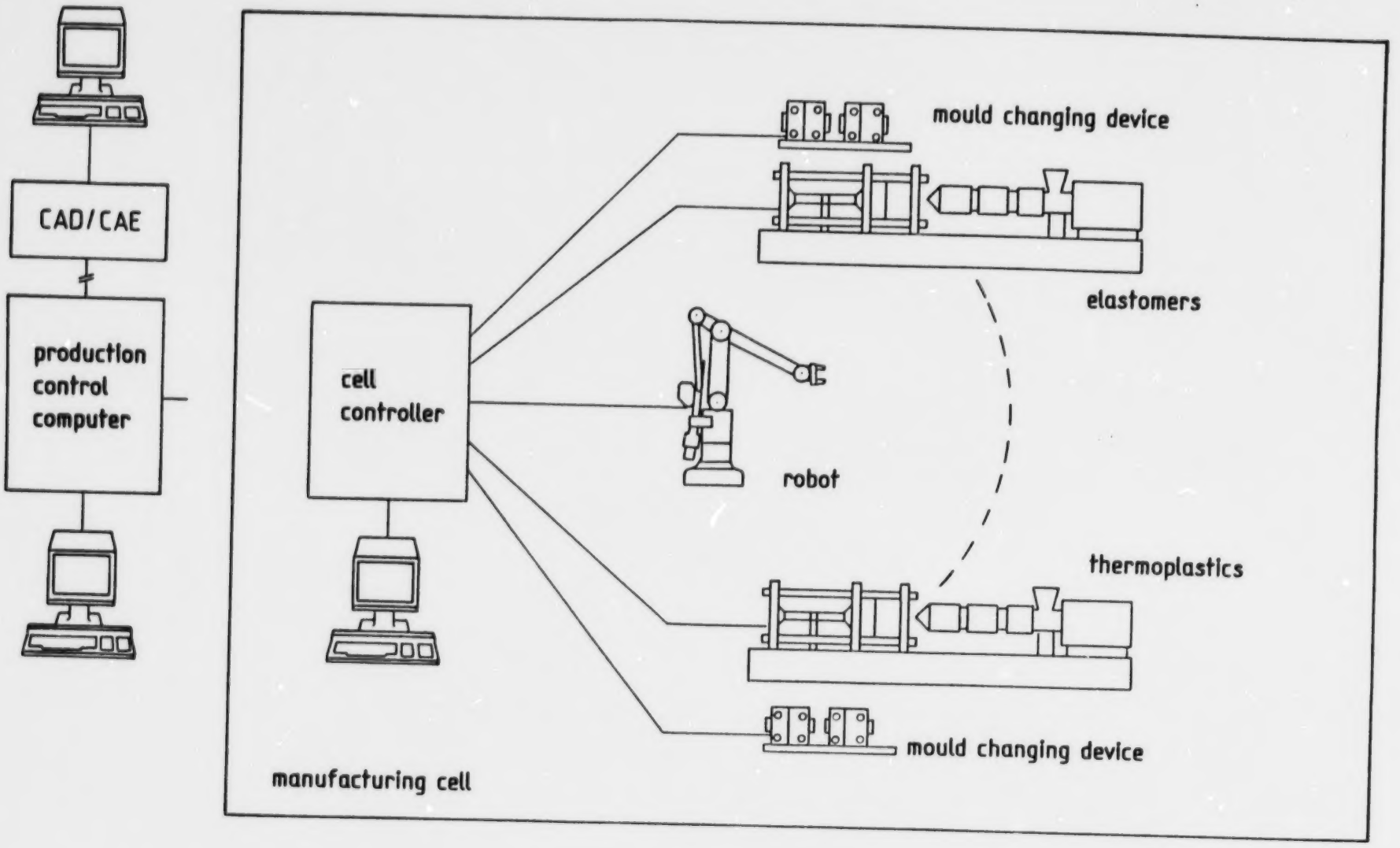
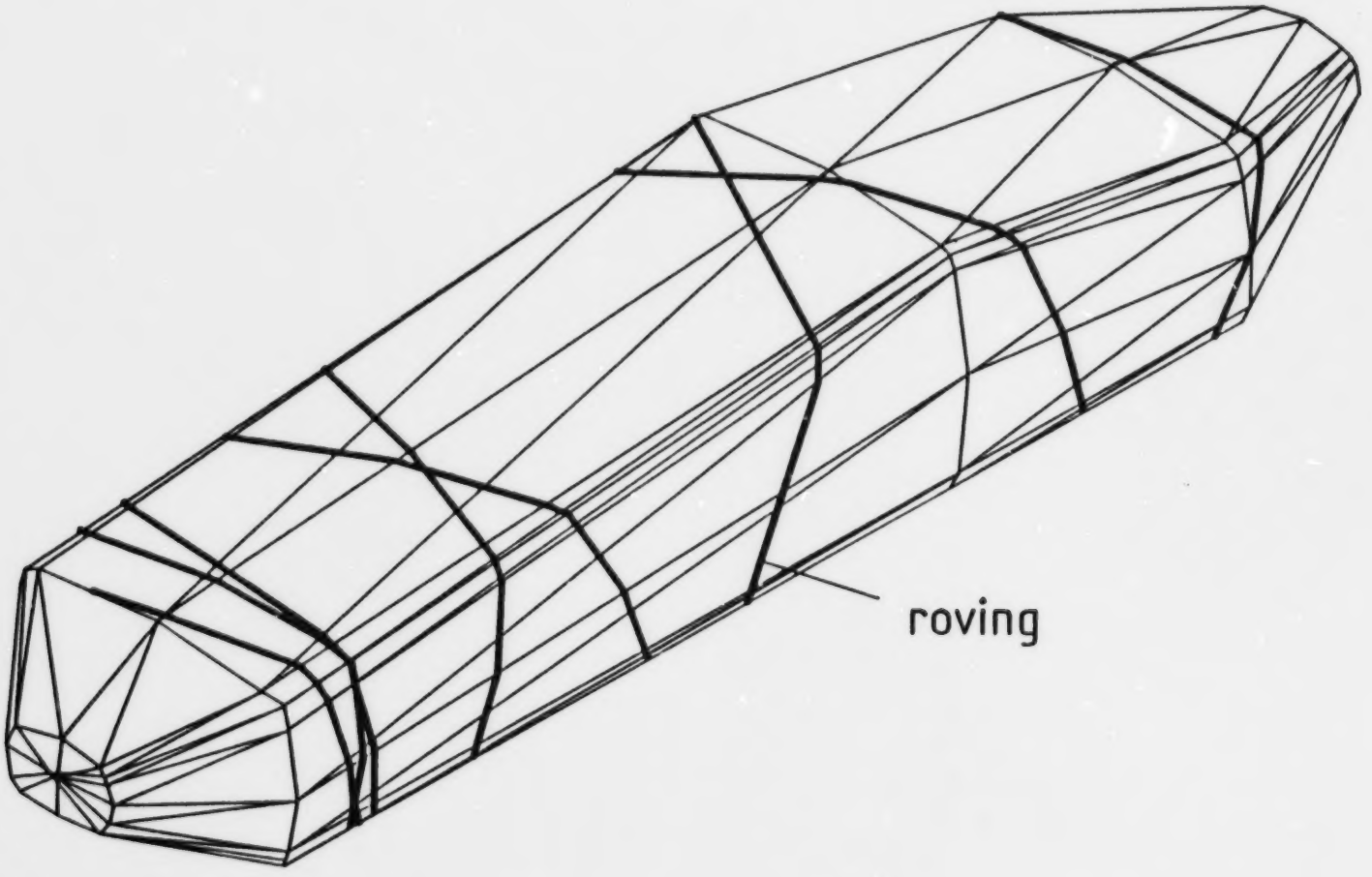

CAD/CAE
production control computer
cell controller
mould changing device
elastomers
robot
thermoplastics
mould changing device
manufacturing cell

Figure 6



simulation of filament winding for a robot arm

Figure 7

Near-net Shape in Manufacturing Technology - Metals

by

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Columbus Division, Columbus, Ohio

ABSTRACT

Manufacturing parts to shapes and sizes that require very little finishing operations is gaining increasing importance. In addition to understanding the manufacturability of a given geometry by several competing processes, it has become necessary to control the process parameters very closely to produce quality parts consistently.

Net (or near-net) shape technologies were implemented in past years by controlling process parameters and improved tooling technologies. Generally the implementation of these technologies for selected parts in actual production necessitated an unusual amount of trial and error. Understanding the methodology of manufacturing a given part from an engineering drawing or a conceptual design has been making steady progress and has led to the introduction of science and empirical based techniques in production processes. The advent of computer-aided technologies is accelerating this development beyond the state-of-the art.

In this presentation, in addition to describing a commonly accepted methodology of designing and implementing a process for net-shaping a given part, some specific examples of application of this technology in industrial practice will be covered.

PROCESS SELECTION FOR CO-CR-W-C-B MATERIALS

R. J. Dawson, Deloro Stellite Inc.

INTRODUCTION:

Co-Cr-W-C-B materials have a useful combination of wear, heat and corrosion resistant properties. Applications include metal-on-metal wear, cavitation, erosion, corrosion-abrasion and cutting edge service. This presentation will examine the processes used for Co-Cr-W-C-B component manufacture, in terms of their capabilities, advantages and limitations. It will be seen that in addition to economy of scale and dimensional considerations, that the microstructure and properties of these materials are strongly influenced by process selection. We are in the early stages of computer integration, but several examples will be shown to illustrate how we use computers to design, monitor and control our process.

MATERIAL CONSTITUTION:

The constitution of these materials can be rationalized by examining the liquidus diagram and isotherm given as figure 1. The most popular chemistry is 1.2% C, 29% Cr, 5.2% W, 2.8% Ni, 2.8% Fe, 1.4% Si, 0.9% Mn, 0.4% B, Balance Co. The liquidus diagram predicts the formation of cobalt rich dendrites initially on solidification with the remaining liquid becoming enriched in carbon until a eutectic composition is reached. Solidification is completed with the formation of a eutectic mixture of M_7C_3 carbides and further cobalt alloy. The isotherm indicates that further carbide formation can be expected as the solid alloy cools. Commercial materials exhibit these morphologies and contain approximately 40 volume percentage M_7C_3.

The metallic portion of these multiphase materials is essentially a cobalt base superalloy, similar to General Electric's X-45 developed for the hot section of jet engines. This alloy has outstanding hot strength as the result of both solid solution and carbide particle strengthening mechanisms. Nickel and iron are added to enhance ductility, by promoting the formation of metastable, FCC, metallic phase structure. However, large surface strains caused by wear lead to deformation induced transformation of the local metallic phase to HCP. Thus a good combination of surface wear resistance and structural ductility are achieved. The $M_7 C_3$ carbides serve as particle and fibre reinforcement, and also protrude to form a hard abrasion resistance armour when abrasive action is prominent. Examples of microstructures will be shown, to illustrate how the processing routes can be used to alter the distribution of the phases and the material properties.

PROCESS SELECTION - OVERVIEW:

Figure 2 is a schematic fit of the processing options. Each process has limitations in terms of the geometric complexity it can produce and the number of components which can be manufactured economically. For example pressed, powder metallury parts are restricted to small simple shapes and must have large production runs to pay for the tooling and set up labour required. The domains indicated are qualitative only, but they serve as a first guide in process selection.

Dimensional control depends greatly on the process selected. For example

investment casting can produce parts with dimensions controlled to +/- 0.005", whereas hardfacing by fusion is generally limited to dimensional control of +/- 0.03". Specilized machining and grinding techniques are available for these materials giving dimensional control of +/- 0.0003" or better. Since these materials are difficuly to machine, there is a significant financial incentive for near net shape processing.

COMPUTER SYSTEM:

We use a central computer to monitor and control our sales, engineering, purchasing, manufacturing and quality functions. Table I outlines the use of the system from the stage of customer enquiry, through planning, manufacturing, shipping and payment. Since we ship some 200 different components a month, this type of job tracking is essential. In addition to the cited functions, the data base is used to study our manufacturing system to estimate the impact of process and product line changes. The data base also serves as a powerful tool for business forecasting and budgeting.

We have removed most of the drawing boards from our planning department and now produce all our drawings using AUTOCAD. We have experienced improved labour efficiencies, better drawing quality and simplified design revisions, since the system was installed four years ago. We also use AUTOCAD to generate tapes for our numerically controled machine shop equipment. Almost all our reporting is typed using word processors, and interdivisional mail is now done electronically.

CASTINGS:

Co-Cr-W-C-B materials are generally air induction melted at 1500°C and cast into refractory moulds to form components. Common moulding systems include investment, resin shell, sand graphite permanent and centrifugal. Typical casting weights and dimensional tolerances, are:

a) Investment +/- 0.005" per inch; up to 60 lb

b) Resin Shell +/- 0.010" per inch; up to 80 lb

c) Sand Moulding +/- 0.030" per inch; up to 1500 lb

These moulding processes are well described in ASM metals handbook, volume 5 eigth edition, but each has its advantages. Investment moulding is ideally suited for intricate components requiring tight dimensional control and surface finish. Valve cages, impellors, glass mould funnels and extrusion die inserts are typical applications. The weight restriction, labour cost and slow solidification rate are disadvantages of this process. Carbide spacing is inversly proportional to square root of the cooling rate. Investment cast microstructures are coarser and more open, than sand cast and shell cast structures, due to differences in solidification time. The coarser widely spaced carbides are preferable when handling coarse abrasive, but the open areas are more accessable to extremely fine abrasives.

Sand moulding is best suited for large components which do not require tight dimension control or smooth, as-cast surfaces. Pump casings, elbows, bushings and rollers are typical applications. Labour and tooling costs are significantly reduced for most sand moulded components.

Centrifugal castings are very dense and free of pores and inclusions, due to the centrifugal forces and directional solidification of this process. Cylindrical shapes are ideally suited for this process with examples being sleeves, bushings, rollers and valve seats. The use of graphite and steel moulds also gives extremely fine carbide spacing. The majority of centrifugal castings are used in the machined condition.

Recently we have purchased software from Foseco, U.K., which allows computer simulation of the solidification process. The location and extent of shrinkage porosity can be accurately displayed, and riser modifications can be designed and evaluated on the computer. We are expecting significant improvements in our scrap rates, yields and on-time delivery performance, do to this technology.

WROUGHT PROCESSING:

Technology has been developed to hot forge, hot roll, form roll and press form Co-Cr-W-C-B materials. Processing is similar to tool steels and superalloys as outlined in ASM metals handbook, vol. 14, ninth edition. During forging and subsequent hot working the eutectic carbide network is broken down, to form a dispersion of descrete rounded carbides. The wrought material has tensile elongations of 10 to 17%, compared to 1% or less most castings.

Wrought Co-Cr-W-C-B materials are favoured where fracture and mechanical integrity are prime concerns. Typical applications are Aerospace Bushings, Shafts, Knives and Reaction Vessel Walls. Plaze, Sheet and Rod are

produced in standard sizes. Roll forming is ideally suited to manufacture erosion shields to protect turbine vanes from steam droplet erosion. Half sleeves are produced by press forming, and fine application for quick repair of shafts.

POWDER METALLURGY (P/M):

Specialized techniques are necessary to manufacture Co-Cr-W-C-B components by powder metallurgy, since compacts have almost no strength as-pressed. The overall process is as follows.

1) Gas atomization to 44 micron size powder
2) Blend, mix, binder
3) a) Mechanically press
   b) Cold extrude
   c) Injection mould
4) Fixture
5) Debinder
6) Vacuum sinter using liquid phase sintering to achieve 98 to 100% density

P/M products are produced to tolerances of +/- 0.003", with good surface finish, and free of macroscopic defects. The process is particularly economical for long production runs (>5000 pieces) of simple shapes such as bushings, balls, saw teeth and scissor inserts. Tooling and set up costs preclude the use of P/M for short run applications.

Extremely fine mircostructures can be achieved by P/M and this has proven to extend life under fretting and cutting applications, compared to castings with similar compositions.

Statistical Process Control and Statistical Quality Assurance are being used for our P/M process, and this has lead to the use of computers to do statistical calculations and data presentation.

Metal injection moulding of Co-Cr-W-C-B materials is just being commercialized. This process is similar to plastic injection and allows the production of intricate geometries by P/M. We are currently working with NRC-IMRI to adapt their CIMP software to simulate metal injection moulding. We expect to minimize distortion and to optimize mould design using this software.

HARDFACING:

Co-Cr-W-C-B materials are used extensively as coatings to prevent wear of less resistant substances. Table II shows the variety of deposition methods which can be used. Hardfacing allows the designer to put Co-Cr-W-C-B material in high wear areas, while selecting a substance for different reasons such as price, toughness, thermal conductivity or pressure vessel requirements. The American Welding Society's Welding Handbook provides a good description of these processes. Coatings can be mechanically bonded or full fusion deposits with 5 to 40% base metal dilution. Solidification rate and deposit chemistry vary significantly dependent on the process, hence microstructure and wear resistance vary with the process selected. These processes can also be used for reclaiming worn components.

Typical applications include the following:

1) Plasma transferred arc welding of valve seats, extruder screws and paper slitters.

2) Oxyfuel hardfacing of carpet knives and auger tips.

3) Flame spray coating of agitator shafts, mixer paddles and fan blades.

4) Submerged arc rebuilding of hot working rolls.

There is an increasing use of computer control and robotic manipulation for hardfacing. This is particularly true for capital intensive, automized systems for high production work, such as engine valves.

CONCLUSION:

Co-Cr-W-C-B materials are difficult to process due to their multiphase structures, but a variety of processes have been developed to manufacture components. Process selection depends on geometric complexity, number of parts to be made, overall component cost, dimensional tolerances and microstructure best suited to resist the wear environment. We are in the early stages of computer integration, but computers are increasingly important in all aspects of our business.

RD/km
August 4, 1988

TABLE I

CENTRAL COMUPTER SYSTEM FOR SALES, ENGINEERING, MANUFACTURING PURCHASING QUALITY AND ACCOUNTING

INPUT	PROGRAM	OUTPUT REPORTS
- request for quotation	- preplanning - estimating - pricing	- quotation to customer
- order entry	- planning - costing - scheduling	- job travel card - bill of materials - job cost budget
- time cards - material requisitions - purchase orders - scrap tickets	- shop floor control	- expediting report - job tracking - quality cost reports
- order achievement	- job closing	- job cost variances - transfer to finished goods - shipping documents
- order shipped	- invoicing - receivables control - inventory control	- invoicing customer - days outstanding on receivables - inventory adjustments and variances
- payment received	- receivables control	- adjustment of receivables

TABLE II

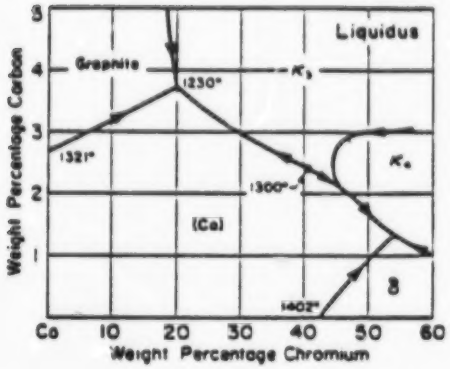
WELDING PROCESSES USED FOR HARDFACING AND RECLAMATION

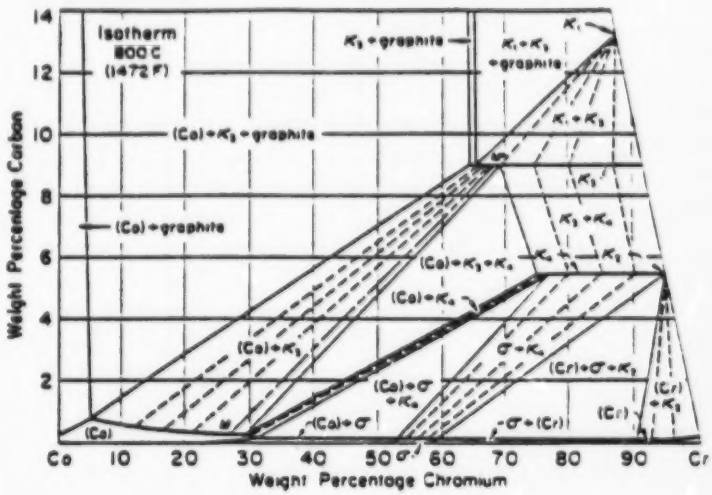
Arc Welding Processes	Thermal Spraying	Other Processes
Shielded Metal Arc	Flame Spraying	Oxyacetylene Welding
Flux Cored Arc	Plasma Spraying	Laser Cladding
Submerged Arc	Electric Arc Spraying	Brazing
Gas Tungsten Arc	Detonation-Gun Process	Resistance Welding
Gas Metal Arc	Jet Kote	Friction Surfacing
Plama Arc		
Electroslag Welding		

FIGURE I

C-Co-Cr (Carbon-Cobalt-Chromium)

By J. M. Drapier and D. Coutsouradis





The diagrams for the C-Co-Cr system presented here show the liquidus surface in the cobalt-rich corner, from Thompson and Lemkey (1), and the isothermal section at 800 C (1472 F), from Köster and Sperner (2). *(Continued on next page)*

Constitution of Ternary Alloys

C-Co-Cr (Carbon-Cobalt-Chromium), continued

Köster and Sperner have indicated a eutectic that extends from a quasiperitectic at 1300 C (2372 F), where $L + \alpha_4 \rightarrow (Co) + \alpha$, to a ternary eutectic at 1230 C (2246 F), where $L \rightarrow (Co) + \alpha +$ graphite. Lemkey and Thompson (3) report that alloys on this liquidus line pass through a monovariant ternary eutectic reaction $L \rightarrow (Co) + \alpha$. This reaction is illustrated on the diagram showing the liquidus surface in the cobalt-rich corner.

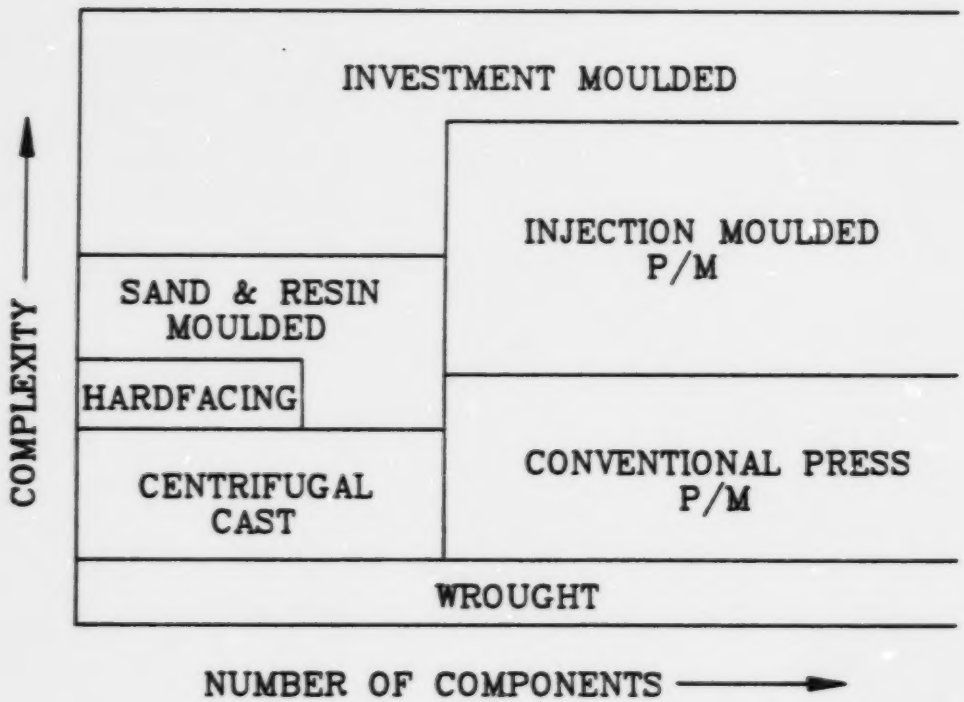
On the isothermal section at 800 C (1472 F), the line *MM'* in the $(Co) + \alpha$ field separates the magnetic from the non-magnetic alloys. The dashed lines represent tie lines.

The phases on the diagrams and referred to above ha the following formulas:

α	Cr_7C_3	α	$(Cr,Co)_7C_3$
α	Cr_3C_2	β	β $CoCr$
α	$(Cr,Co)_7C_3$	σ	σ $CoCr$

1. E. R. Thompson and F. D. Lemkey, *Met Trans*, Vol 1, Oct 1 p 2799-2806
2. W. Köster and F. Sperner, *Arch Eisenhüttenw*, Vol 26, 1 p 335-339
3. F. D. Lemkey and E. R. Thompson, U. S. Patent No. 3,364,0 June 4, 1968

FIGURE 2



SCHEMATIC FIT OF MANUFACTURING PROCESSES